An Analysis of Growth and Mortality of Planted Indigenous Tree and Shrub Species in Tiromoana Bush.

by

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Study Area Map:

Introduction

Tiromoana Bush, a 410 hectare coastal lowland forest/ecosystem restoration area (also known as Kate Valley Conservation Management Area), was created in 2005 in conjunction with establishment of the Kate Valley landfill operation, and as a legal condition implemented by the Environment Court in 2004 (Smith 2004) in exchange for granting the resource consent enabling the landfill to operate over both its intended 35 year operational term and for the 30 year period after that in which aftercare operations are required (Korhonen 2020). The purpose of creating the reserve and restoring it from existing remnants, was both to mitigate the loss of some small patches of native vegetation present on site prior to construction of the landfill, particularly a small (0.73 ha) remnant patch of Black beech (*Fuscospora solandri*) forest (Remnant "A") and its associated flora. The restoration project was also intended to provide a broader social good by restoring/expanding what is a rare ecosystem type in the North Canterbury region: Coastal Lowland forest (Singers & Rogers); and to allow for the creation of a series of walking tracks and amenities within the reserve to allow the public to utilize it. The conditions of the resource consent also require Transwaste to provide long-term funding to continue track maintenance and ongoing restoration work (planting, fencing and pest control) for the reserve into the future, 30 years beyond the term of the Landfill (Korhonen 2020).

The initial 5-year restoration plan (currently a 3rd iteration is in effect) divided the reserve into seven distinct zones, with planting focussed on the 8 hectare area surrounding existing black beech remnant "B" (Zone 1), the inland faces surrounding Kate pond in a 107 hectare area (Zone 2), the 17.2 hectare Kate valley flats, which include wetland areas (Zone 3), and the 14 hectare lower portion of Kate valley adjacent to the coast (Zone 5) (Norton 2005). This study focusses solely on permanent sample plots in restoration plantings, which were established solely in Zones 2, 3 and 5, as well as some individual Black beech (*Fuscospora solandri*) and Kahikatea (*Dacrycarpus dacrioides*) plantings occurring in Zones 2 & 3.

The 2005 restoration plan envisaged a minimum of 5 hectares of new plantings being established during the first 5-year term, with a minimum survival target of 50% (Norton 2005); the subsequent restoration plan drafted in 2007 had an alternative objective, with a target of establishing an additional 3000 seedlings/annum plantings, but providing a new focus on the valley bottom aiming to create a kahikatea-dominated forest in the longer term by requiring >50% of plantings to be established in that area (Norton 2005). This change was due to some plantings comprising edge-planting and strips, which were hard to quantify in terms of area. A separate objective also existed to consolidate the beech remnant (Remnant "B") in zone 1 and the new beech plantings which had been created in zone 2, as well as establish a new beech planting site if possible (Norton 2005).

Restoration work in the initial 8 years (first restoration Plan period) has also included construction of a deer proof fencing around the entire perimeter of the reserve (Norton 2012), as well as some internal low fencing around individual plantings to deter feral pigs (*Sus scrofa*) and hares (*Lepus europaeus*), as well as active control of pest animal species (browsing animal and also those predacious to avian life) occurring semi-annually. It was noted in the initial Plan that the perimeter deer fence would be unlikely to prevent feral pigs from accessing the reserve area and that pigs in particular would pose a threat to plantings (Norton 2012).

The planting sites range in age of establishment from 2006 to 2012, with a range of species present at each site appropriate to its relative site, aspect, and slope position. The success of the plantings was intended to be assessed through PSPs co-located at each planting site (Norton 2005) for mixed plantings. The PSPs were generally (although not always) of 100m^2 size and demarcated with steel corner posts and with all trees tagged and measured for height at planting, and various times afterwards. There are also a small number of tagged individual trees clustered within the unbounded plantings of Black beech and kahikatea which were similarly remeasured in the early years following planting[1].

Abiotic factors impacting growth/survival of the plantings include frost at low elevation sites and drought (moisture stress), with management strategies for the plantings to address these factors having been late-winter planting to ensure the worst of the early frosts have been avoided, and that adequate root growth occurs in the first growing season to enhance survival in drought conditions (Norton 2005).

Biotic constraints for the broader area are mainly: animal browse and mechanical damage (from feral pigs, hare and deer) prior to fencing of the reserve and to a lesser degree afterwards for pigs; moisture competition and enhancement of frost damage from surrounding grass species (Norton 2005); and whether planted stock have appropriate fungal mycorrhizae to thrive on the site. Management strategies to address these issues are the fencing and ongoing active pest control, chemical release of surrounding vegetation prior to planting, and inoculation of seedlings with mycorrhizae respectively (Norton 2005).

The site elevation of all of the sampled plantings is minimal across the site as a whole (sea level to 175m approximately) and unlikely to be a primary factor affecting growth/mortality, although slope and aspect, which may influence growth, vary widely by site.

Overall the remeasurement of the PSPs and individual plantings has allowed for calculation of conservative estimates of Height, Ground line diameter (GLD) and Diameter at Breast Height (DBH) growth of the various planted species and provided an indication of which levels of stocking and species compositional mixes are most successful for the sites the PSPs and other plantings represent. Crown closure estimated from drone photography, and the presence of naturally regenerated seedlings at some sites can also give an indication of the longer-term success of the sites.

A secondary exercise in calculating above ground biomass (AGB) from various form-specific equations (Conti et al. 2019) and general averages for estimating below ground biomass (BGB) and AGB/BGB carbon ratios, has also provided a conservative estimate of carbon stored per hectare. Re-tagging of the all the species measured during the study will allow for future remeasurements to proceed with greater data precision and accuracy.

Summary of Planting areas represented by Permanent Sample Plots (PSPs)

2006 Plantings

The 2006 plantings covered by the PSPs comprise one site, with one PSP, Plot 6-2, which represents a north-facing, moderately steep lower/toe-slope site adjacent to Kate pond, a small artificial lake within the reserve. The site appears to be free-draining and subject to moisture stress which (from both the slope and increased sun exposure from the aspect), is likely to have had and continue to have, an impact on all plantings. Plot 6-2 is $100m^2$ (10m x 10m) and located on the south side of a clearing adjoining the lake.

2008 Plantings

The 2008 plantings are on 2 discrete sites with 3 PSPs (8-1, 8-4, and 8-5). 8-1 represents a slightly sloping North facing toe-slope directly adjacent to Kate Pond (ie: Southern edge), with the site being

[1] See "Study Area Map", page 2

of high soil moisture and slow draining. This plot is $100m^2$ (10m x 10m) and is located just above (south of) the South-East edge of Kate pond. The greater planting area has perimeter fencing (3 wire plus mesh) on the West, South and East sides, with the pond on the North side.

Plots 8-4 and 8-5 are across the valley to the North-East from Kate Pond, and are located adjacent to each other in a South-facing fan wedged between two small hills covered in naturally regenerating Kanuka (pre-restoration). The site has low-moderate steepness (25.8% slope), and the broader area of the planting appears to have been a debris fan from a slip from one or both of the adjacent hills. Both Plots are $100m^2$ (10m x 10m), but 8-4 and it's surrounds on the North, East and South sides) is comprised entirely of new plantings, whereas 8-5 slightly to the West and it's immediate surrounds in a small area comprise a combination of transplanted plantings rescued form Remnant "A" and new plantings.

2011 Plantings

The 2011 plantings are located on 3 sites: a flat, grassy valley bottom; a mildly sloping toe-slope; and a an upper-mid slope site. All 3 PSPs have irregular shape and utilise fence lines as one boundary (Northern boundary for plot 11-1, Western boundary for plots 11-3 and 11-4), with plot sizes being $126m^2$, $96m^2$, and $91m^2$ respectively. The broader site encompassing all 3 plots, and surrounding plantings, starts at the flat valley bottom and rises to the steep upper slope of a small hill before planting terminates.

2012 Plantings

The 2012 Plantings comprise two $100m^2$ plots (12-1 and 12-2) located at the coastal edge of the reserve in a narrow, deeply-incised gulley. 12-2 however is located on a steep, North-facing exposed mid-slope, whereas Plot 12-2 is located on a lower/toe-slope at the base of the gulley with a more easterly aspect and considerably more surrounding shelter. It also has a greater degree of soil moisture given both its slope-position and relative slope.

Kahikatea Plantings

10 Kahikatea were planted in winter 2006 at the North-eastern edge (South West-facing) of Kate Pond, with all tagged and re-measured for height (in cm) in 2006 (spring), 2007, and 2008. These do not represent all kahikatea planted within the reserve as the number of such has been extensive, but they have been the most successful with regards to growth and survival (all having survived since planting), and were the first kahikatea planted. As such these plantings represent the potential growth of Kahikatea on an ideal site within the reserve. It is however difficult to quantify the data with high confidence given the small sample size (n=10).

Black beech Plantings

Three different sites were planted with differing numbers of Black beech (*Fuscospora solandri*) to meet long term Plan objectives to re-establish Black beech within the reserve. These sites differed in density and surrounding species as there was an intent to test the viability of different planting strategies. The sites comprised a North-facing mixed species planting (n = 16) noting that beech has been document to have greater growth success in mixed plantings (Tulod & Norton 2019), a South-facing mid slope (n= 21) planted at low density and with very few surrounding species, and a fenced ridgeline site (n=93) where the beech were interplanted with a nitrogen-fixing nurse crop of tree lucerne (*Cytisus proliferus*) and provided with piped irrigation at the early stages following planting. A recent study conducted by the author in 2020 found no statistically significant difference in height or DBH growth between the 3 sites (Kernahan & Morice 2021) even accounting for the slight variation in planting year, possibly reflecting the similar growing conditions of all of the sites and/or the irrigation/nurse crop on the exposed ridge site offsetting it's abiotic limitations to allow the beech there to match the growth observed on the other two sites.

Methodology:

The Plots were primarily intended to measure initial planting success, and generally have not been remeasured in the past 6-10 years. As such, some plots could not be located (where posts had fallen down, or in the case of a slip for one plot). With the focus of this study being growth of tree species, all plots containing predominantly trees were attempted to be located, with 9 viable plots being found (a 10th plot was found but had been destroyed by a small land slip). Some original tags were identified within each plot, and growth could be directly calculated for these trees, but in general, averages of measurements taken in the past and those taken during this study were used as a more viable surrogate for estimating performance, given the greater sample size of individuals.

Separate plantings of individual species were not generally tagged or measured at time of planting except for a small group of kahikatea near the Kate pond edge where all trees were tagged and measured (these being located during 2021 remeasurement), and similarly for an early trial planting of Black beech, the tags of which could not be located. As such, for the beech plantings, average measurements from the unlocated trial plot, and from the new measurements were used for comparison. In all cases for the unbounded plantings, estimates of growth were averages for the total number of sampled trees and not reflective of an area multiplier (eg: "per hectare").

In all cases, as ground line diameter (GLD) was not originally recorded, and is not in any case standardized for each species in the nursery's provided stock, a general range based on observation of seedlings at the nursery (Cavanaugh 2021) was used when calculating GLD increment growth, with the upper end of the range used to ensure a conservative estimate was calculated.

PSP re-sampling

Steel plot corners and/or plot corner points on fence lines were first identified and marked with blue flagging tape. Plot boundaries were then laid out with 2 x 20m fibreglass measurement tape to facilitate more accurate identification of "in/out" trees. Photos were taken at corner points along boundary lines and at diagonals towards the plot centres. Lastly drone photography was used to determine crown cover/closure of the PSPs across their extent using the approximate location (where visible) of the marked plot corners to guide photo extent.

Photo scale was calculated using the below formula and converted to the common unit of centimetres (cm):

$S_p = f : H$

<u>Where:</u>
S_p = Photo scale
f = Camera focal length[2]
H = height above ground level (AGL)[3]

[2] Source: DJI Mavik Pro User Manual
[3] Automatically calculated by the DJI Mavik Pro Drone using terrain mapping and GPS altimeter

Crown diameters were then estimated using measurements versus the photo scale by plot, for those species where crown diameter was used to calculated AGB and carbon. This was done by overlaying the drone photos with a an appropriate size grid (usually a 10 x 10 grid with each grid of 4 corners representing $1m^2$) with intersections counted to determine crown closure (eg: number of intersections intercepting vegetation versus total of 121 intersections for a 10m x 10m plot) and approximate crown diameters estimated for species where it was required to calculate above ground biomass (AGB).

All re-sampling

Individual trees were checked to determine if an original aluminium number tag was still present, and if not, a replacement tag was assigned and place at as close to breast height (1.4m) as was practical, or close to the base of the main stem if not. Tags were located at the uphill side for sloped sites and placed using 50mm nails to allow for further tree diameter growth without the tag being outgrown.

After tagging the trees were measured for GLD in of the primary stem, diameter at breast height (DBH at 1.4m) where applicable, and height. GLD and DBH were recorded in centimetres, and height in metres, with all converted to the common unit of centimetres (cm) for analysis.

Multi-stem trees (trees forking below DBH height) were tagged once on the primary stem, being the stem with the greatest height and/or DBH and other individual stems also recorded for DBH and height and measured left-right from the primary stem. Multi-stem trees were noted as such on plots cards

Animal damage was recorded once per tagged stem (primary stem) reflecting the origin of the multi-stem tree as a single original planting. Lastly, site aspect, and the height/composition of competing vegetation was noted

Data treatment

Plot and Individual tree measurement data was analysed in Excel and R to create descriptive statistics. However, given the small number of plots and diverse nature of the plantings it was not possible to conduct comparative statistical analysis such as ANOVA. The purpose of the analysis was instead to identify trends within the period since planting and infer relative success of the different plantings now and moving forward. Pie charts of percentage species composition for each Plot sampled at time of planting and at time of remeasurement, and Boxplots of height, GLD and DBH ranges were created for each planting year grouped by species, for general comparison of the same-year plantings. <u>DBH and height were analysed for the main stem of each tree/shrub only </u>(tallest and/or largest stem) given the number of multi-stem trees with numerous stems[4]. Aggregated height measurement data (for which records exist at various points at and/or since planting) was graphed in scatterplots for each planting year-group by species, with a LOESS lines fitted to identify general trends.

Crown closure was estimated using drone aerial photography of the sampled plots (but not individual plantings which were not area bound) and used as another measure to evaluate planting success. This photography was also used to estimate crown diameter (CD) for those species whose form required CD to calculate above ground biomass.

[4] Although the DBH measurements for all stems was captured where they were greater than 2cm and noted where <2cm. Height measurements were captured where different the main stem.

The periodic annual increment (PAI) for the period between planting and measurement was calculated for Height, GLD and DBH; and the results used to gauge the success of the sites versus each other and existing literature (Pardy et al. 1992).

Lastly, a conservative estimate of carbon sequestered was calculated using a combination of methods. A meta-study providing optimal equations for calculating AGB from tree form (Conti et al. 2019), a lower-limit average percentage BGB for New Zealand tree species from a previous study of 25% (Coomes et al. 2002), and a generally accepted/used conservative figure for converting AGB+BGB to carbon sequestered of 50% of the AGB/BGB total (Beets et al. 2012).

The AGB formulae used varied depending on tree form, with four equations used:

- Type 1 equation for unistem trees with a measurable DBH
    - AGB (kg) = 0.0673*(0.4*(DBH^2)*(Height/100))^0.976
- Type 2 equation for multistem trees/shrubs of consistent canopy dimensions
    - AGB (kg) = EXP(-2.281+(1.525*LN(GLD))+(0.831*LN(Crown diameter))+(0.523*LN(Height/100)))
- Type 3 equation for irregular shaped multistem trees with large branches and irregular crown shape (Ngaio only)
    - AGB (kg) = (EXP(2.474*LN(GLD)-2.757))*1.0787
- Type 4 equations for shrubs and younger seedlings <1.4m tall
    - AGB (kg) = EXP((-0.37+(1.903*(LN(Crown diameter)))+(0.652*(LN(Height/100)))))*1.403

All equations with GLD, DBH and Height in centimetres , and Crown diameter in metres.

Results:

2006 Plantings

Stocking and Composition

Plot 6-2:

The total initial stocking was 6200 SPH (Table 1), comprising a relatively even mix of kohuhu (*Pittosporum tenuifolium*, 26%), tarata (*Pittosporum eugenoides*, 32%), manatu (*Plagianthus regius*, 24%) and tī kōuka (*Cordyline australis*, 15%), with a small component of puahou (*Pseudopanax arboreus*, 3%) (Figure 1).

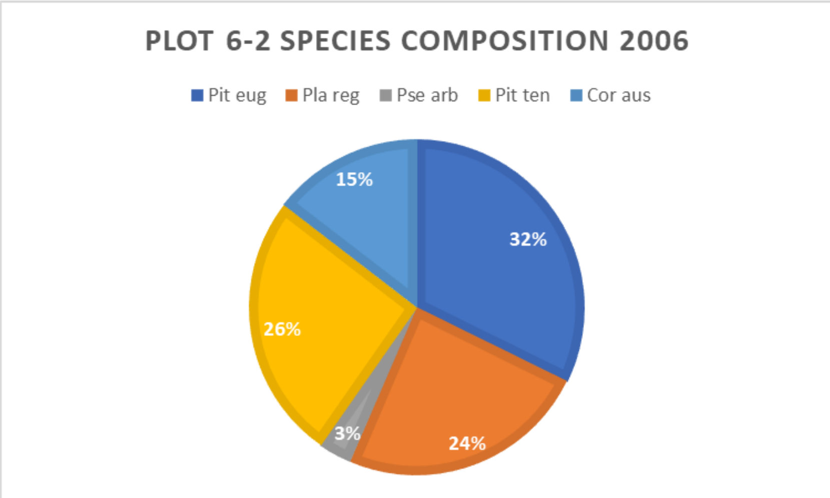

Figure 1: Plot 6-2 species composition at time of planting (2006), percentage of total stocking (6200 SPH).

Current total stocking has declined by 50% from 6200 SPH to 3100 SPH (Table 1) , with manatu becoming the dominant species on the site by stocking, and the other species suffering proportionate mortality, total in the case of the small puahou component (Table 1).

Species	Stocking 2006 # Stems	Stocking 2021 # Stems	Stocking 2006 – Stems per hectare	Stocking 2021- Stems per hectare	Percentage Change (%)
Tarata (Pit eug)	20	4	2000	400	-80%
Kohuhu (Pit ten)	16	9	1600	900	-43.8%
Manatu (Pla reg)	15	15	1500	1500	*nc*
Tī kōuka (Cor aus)	9	3	900	300	-66.7%
Puahou (Pse arb)	2	0	200	0	-100%

Table 1: Species composition and stocking change from planting (2006) to present (2021).

Species composition for the plot as a whole has shifted considerable from 2006 (Figure 1) to 2021 (Figure 2), as seen by the relatively even proportions of the four main species in 2006, versus the dominance of manatu and kohuhu on the site respectively in 2021.

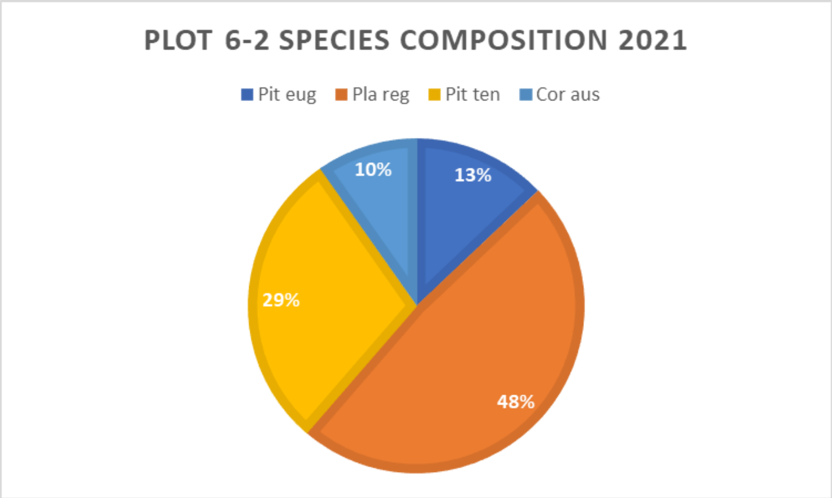

Figure 2: Plot 6-2 species composition at time of sampling (Autumn 2021). Percentage of total stocking (3100 SPH).

The drone photography (Figure 3) indicates 77 intersecting points were counted indicating a crown closure of 64%.

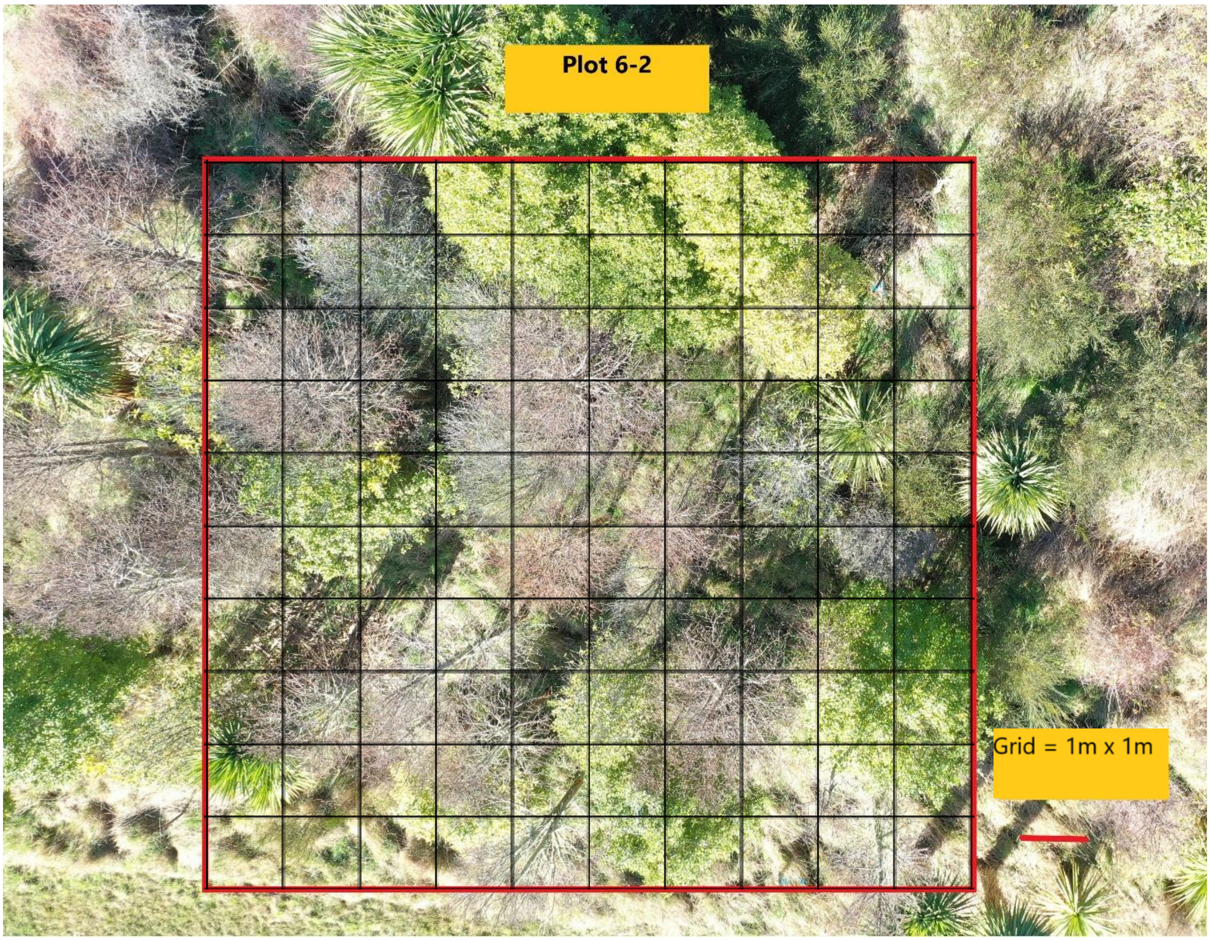

Figure 3: Drone photo of approximate location of Plot 6-2. Note deciduous manatu with limited foliage at time of photo. $1m^2$ grid spacing.

The 3 species having crown diameter estimated for the Type 2 equation were kohuhu, tarata, and any multi-stem manatu. The two *Pittosporum* species both had an average of 4 intersections in each direction, or 2m crown diameter, and the manatu had an average of 3 intersections or 1.5m crown diameter. Counting involved estimation of intersection proportion where sides of crowns were partially across a grid square and not intersecting dots at the crown edges.

Growth and Carbon Sequestration

Summary Statistics – Growth

The manatu had the greatest periodic annual increment (PAI) for the 15 year period since planting for height and GLD (Table 2), followed by the kohuhu and tarata which had roughly comparable growth rates (slight advantage to kohuhu). The ti kōuka generally did not perform well on the site except for DBH growth (2nd) appearing to consolidate further volume growth (via DBH growth) within the relative size they had reached to-date.

Species	PAI Height (cm/ann.)	PAI GLD[5] (cm/ann.)	PAI DBH (cm/ann.)
Tarata (Pit eug)	26.67	0.58	0.25
Kohuhu (Pit ten)	29.11	0.72	0.29
Manatu (Pla reg)	37.11	0.80	0.65
Tī kōuka (Cor aus)	14.73	0.45	0.73
Puahou (Pse arb)	-	-	-

Table 2: 15-year Periodic annual increments (PAI) for Height (cm), GLD (cm) and DBH (cm) for Plot 6-2

The range of measured heights expanded from what was previously measured (Figure 4) for all species except manatu (between 2010 and present) reflecting individual success due to interspecies competition, damage, or genetics over time. Ranges in general though are comparatively narrow (less marginal tails), indicating relatively consistent performance of planted seedlings.

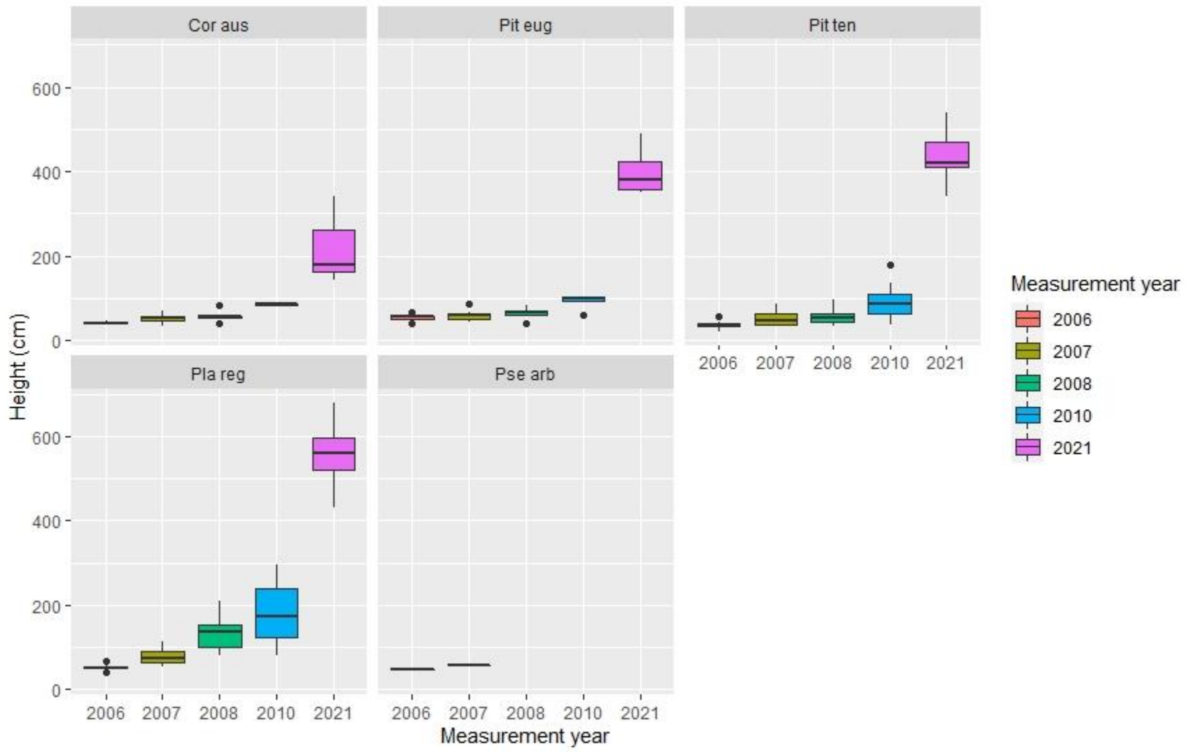

Figure 4: Measured height (cm) vs species/measurement year boxplots.

[5] Original seedling GLD estimated at 0.8cm at time of planting (the upper end of the range observed in the nursery to ensure a conservative PAI)

The LOESS regressions of the height measurement scatterplots (Figure 5) indicate that height growth is still trending upwards for kohuhu and tarata but has largely plateaued for ti kōuka. A very slight downwards inflection in height growth for manatu is also visible, indicating height growth is starting to decline.

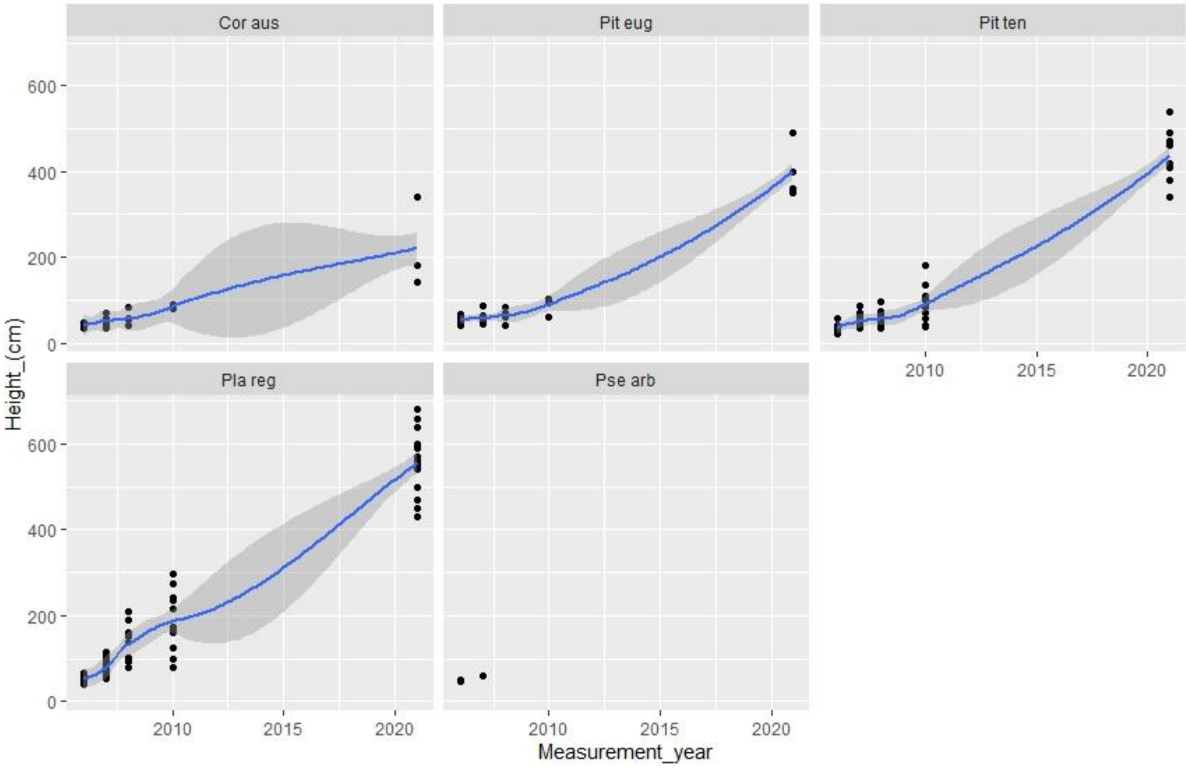

Figure 5: Height growth (cm) vs measurement year scatterplots for Plot 6-2 with LOESS regression lines and confidence interval banding.

GLD ranges for each species at time of measurement (2021) are roughly analogous (when including data tails) despite differing medians (Figure 6) suggesting similar basal growth for each surviving species on the site.

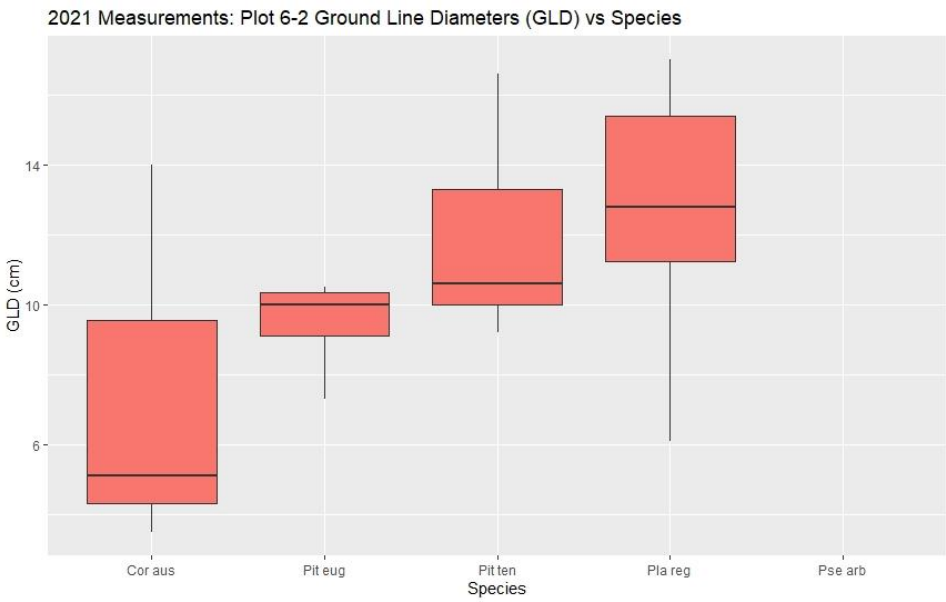

Figure 6: GLD (cm) vs Species boxplots for Plot 6-2 at time of measurement (2021)

DBH ranges (Figure 7) differ between multi-stem and uni-stem trees as expected reflecting the growth pattern of the different forms but given similarity ranges between the same form types again indicates similar growth between species on the site.

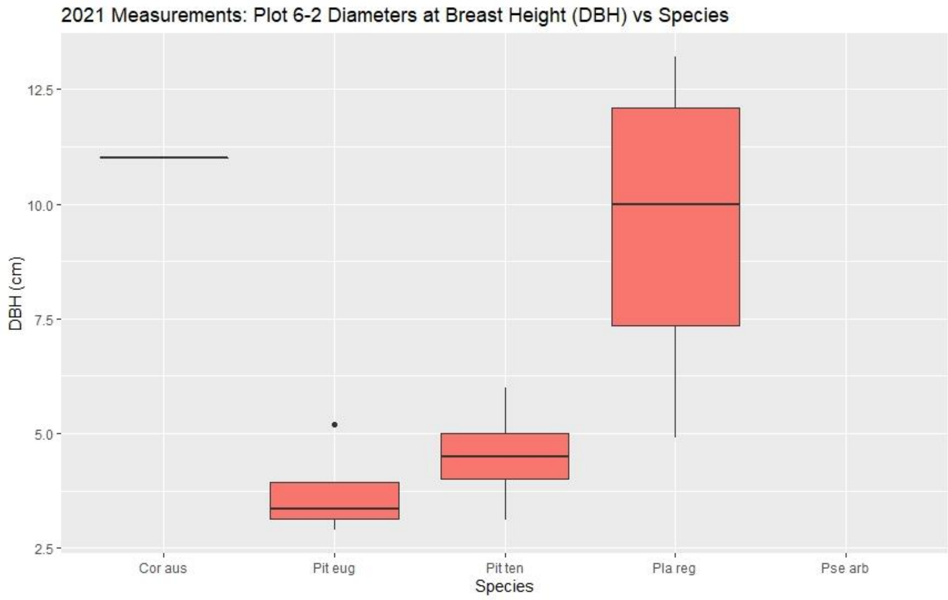

Figure 7: DBH (cm) vs Species boxplots for Plot 6-2 at time of measurement (2021)

Summary Statistics – Carbon

The amount of carbon stored per stem directly correlated with both form and growth rates as expected (Table 3). The kohuhu and manatu having the greatest individual rate of sequestration for the site at 10.43kg and 10.27kg per stem respectively when converted to a per hectare basis.

Species	Average AGB + BGB per Stem (kg est.)	Average Carbon per Stem (kg est.)	# Stems	CO_2 stored (tonnes/Plot area)	CO_2 stored per hectare (tonnes per hectare est.)
Tarata (Pit eug)	14.59	7.30	4	0.11	10.70
Kohuhu (Pit ten)	20.87	10.43	9	0.34	34.43
Manatu (Pla reg)	20.54	10.27	15	0.56	56.49
Tī kōuka (Cor aus)	5.34	2.67	3	0.02937	2.94
Puahou (Pse arb)	-	-	-	-	--
Total (Sum)	**61.34**	**30.67**	**31**	**2.08**	**104.56**

Table 3: Average Above Ground/Below Ground biomass (kg) stored per stem, and total CO_2 sequestered by species per Plot and Hectare.

2008 Plantings

Stocking and Composition

8-1's initial stocking was high at 5100 SPH with plantings predominantly being: manatu, kohuhu, ngaio (*Myoporum laetum*) and tī kōuka; with smaller components of kaikomako (*Pennantia corymbose*) and kowhai (*Sophora microphylla*).

8-4 had an initial stocking of 4900 SPH, with roughly half the area planted in tī kōuka, and the balance in a mix of ngaio, manatu, kohuhu, kowhai and putaputaweta (*Carpodetus serratus*). The canopy closure potential of 8-4 and the similar planting surrounding this plot was always likely to be low given the high proportion of tī kōuka, which has a narrow crown.

8-5 is a densely stocked mix of plantings and transplantings, with the initial stocking of the plot (8-5) was 7000 SPH with a broad mix of tree and shrub species present, including: kapuka (G*riselinia littoralis*) the predominant planting/transplanting by numbers present, tarata, puahou, mingimingi (*Coprosma propinqua*), karamu (*Coprosma robusta*), karamū (*Coprosma lucida*), mikimiki (*Coprosma rotundifolia*), makomako (*Aristotelia serrata*), kanuka (*Kunzea ericoides*), putaputaweta, horoeka (*Pseudopanax crassifolius*), ngaio, kohuhu, kaikomako, and tī kōuka. Kakaha (bush flax – *Astelia fragrans*) was also present but not measured or recorded for the purposes of this research report, which focussed on tree and shrub species only.

Plot 8-1

The total stocking has declined from 5100 SPH to 3700 SPH (Table 4) due to mortality (less possible infill planting) which is, however, still high, but most plantings appear to be vigorous at time of measurement.

Species	Stocking 2008 – Stems per hectare	Stocking 2021- Stems per hectare	Percentage Change (%)
Manatu (Pla reg)	1200	1400	-16.7%
Kohuhu (Pit ten)	1100	600	-45.5%
Ngaio (Myo lae)	900	400	-55.6%
Kaikomako (Pen cor)	400	0	-100%
Kowhai (Sop mic)	300	100	-66.7%
Tī kōuka (Cor aus)	1200	1100	-8.3%
Tarata (Pit eug)	0	100	-

Table 4: Species composition and stocking change from planting (2008) to present (2021).

The plot species-composition has remained relatively stable (Figures 8 and 9) with the exception of total mortality of the small kaikomako component and the addition of a single tarata, which may have been infill planted into a gap post the initial planting.

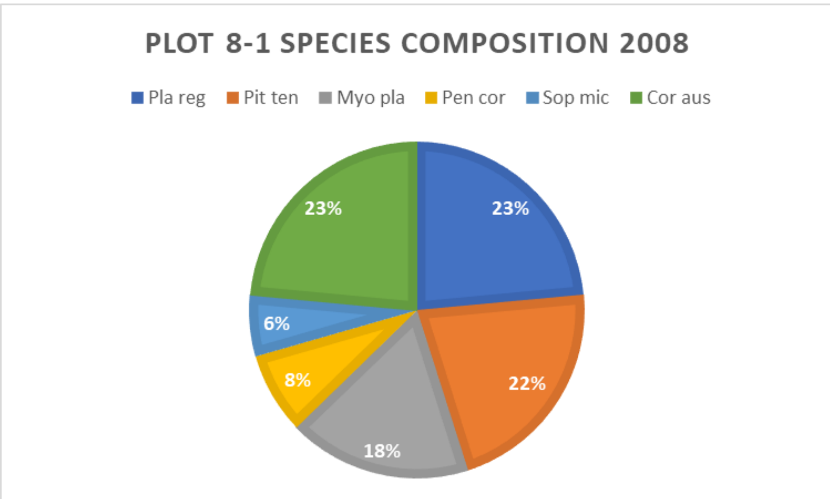

Fig 8: Plot 8-1 species composition at time of planting (2008), percentage of total stocking (5100 SPH).

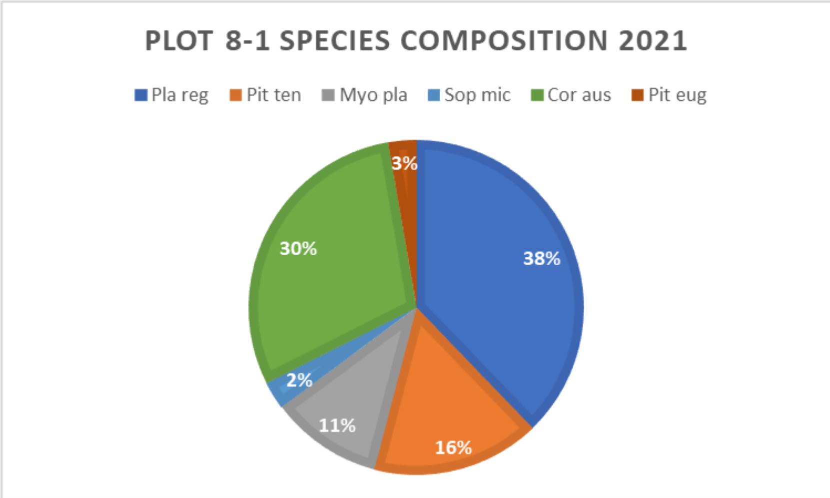

Fig 9: Plot 8-1 species composition at time of sampling (Autumn 2021). Percentage of total stocking (3700 SPH).

The drone photography (Figure 10) indicated a high degree of crown closure (as was observed below the canopy), with 98/121 grid intersections striking crown vegetation indicating a crown closure of 81%.

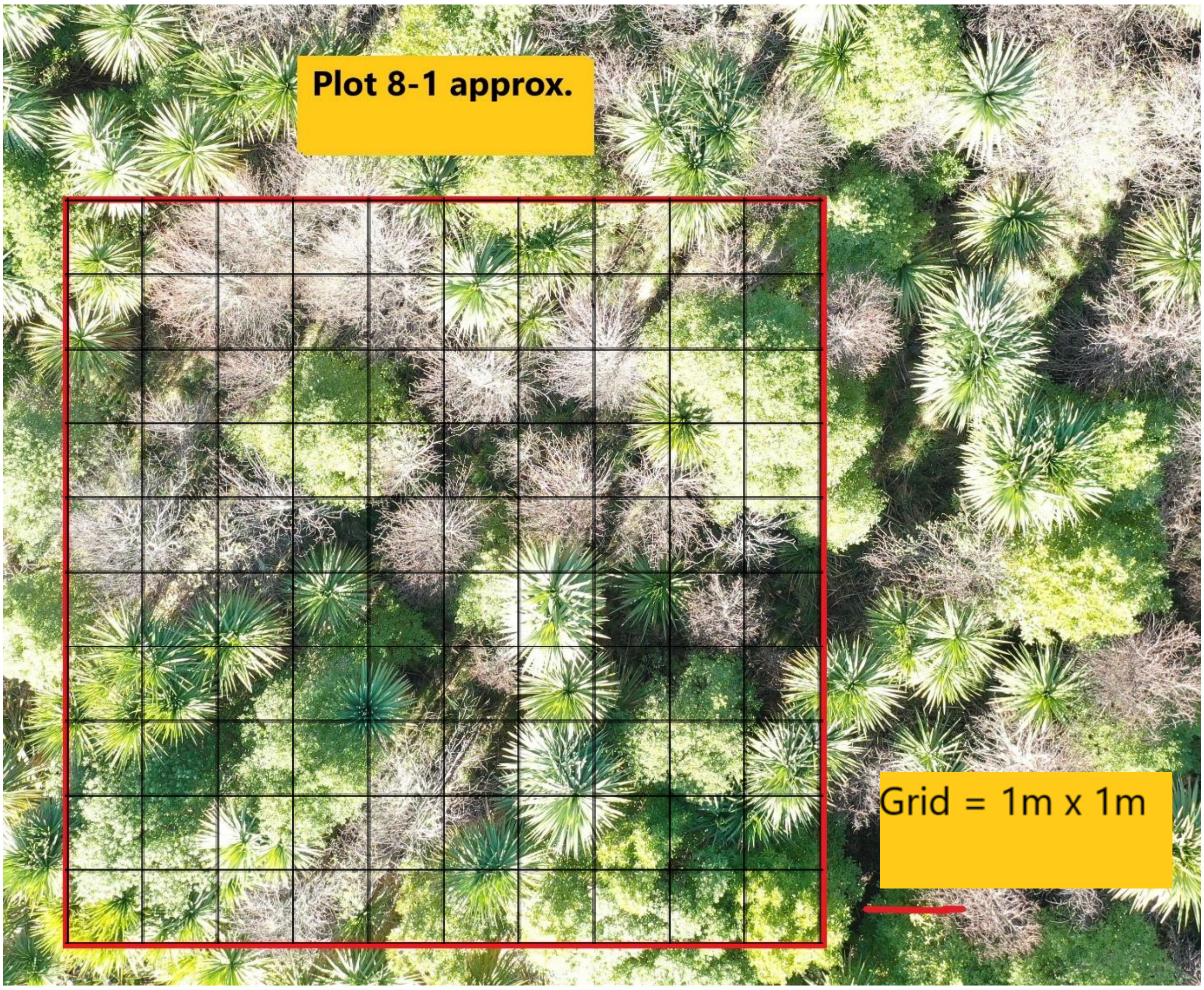

Figure 10: Drone photo of approximate location of Plot 8-1. Note deciduous manatu with limited foliage at time of photo. 1m^2 grid spacing.

Average crown diameter estimates for calculating AGB from the type 2 equation are required for kohuhu and tarata: these are 2m for kohuhu and tarata (4 intersections). Of the other species, ngaio is assessed by the Type 3 AGB equation and requires no CD given its irregular shape, and all kowhai, manatu and ti kōuka are uni-stem and are assessed by the type 1 equation.

Plot 8-4

There appears to have been infill planting into the area of the plot (and surrounding area) following mortality and the plot composition of has changed for the minor component species to include tarata, totara and puahou, and a large increase observed in the ngaio component (Table 5). Putaputaweta is absent presumably through mortality.

Total stocking at present remains similar to initial stocking (4900 SPH) at 4800 SPH (Table 5), reflective of the success of the infill plantings and no subsequent large-scale mortality since that planting.

Species	Stocking 2008 – Stems per hectare	Stocking 2021- Stems per hectare	Percentage Change (%)
Ngaio (Myo lae)	400	900	+125%
Tī kōuka (Cor aus)	2500	2600	+4%
Manatu (Pla reg)	300	300	*nc*
Kohuhu (Pit ten)	700	500	-28.6%
Kowhai (Sop mic)	600	100	-83.3%
Putaputaweta (Car ser)	400	0	-100%
Puahou (Pse arb)	0	100	-
Totara (Pod tot)	0	100	-
Tarata (Pit eug)	0	200	-

Table 5: Species composition and stocking change from planting (2008) to present (2021).

The original composition had a relatively even proportion of all the minor species (Figure 11), but this has seen a shift at time of remeasurement. It is likely due to mortality and infill planting both of alternate species and of greater numbers of ngaio rather than species lost.

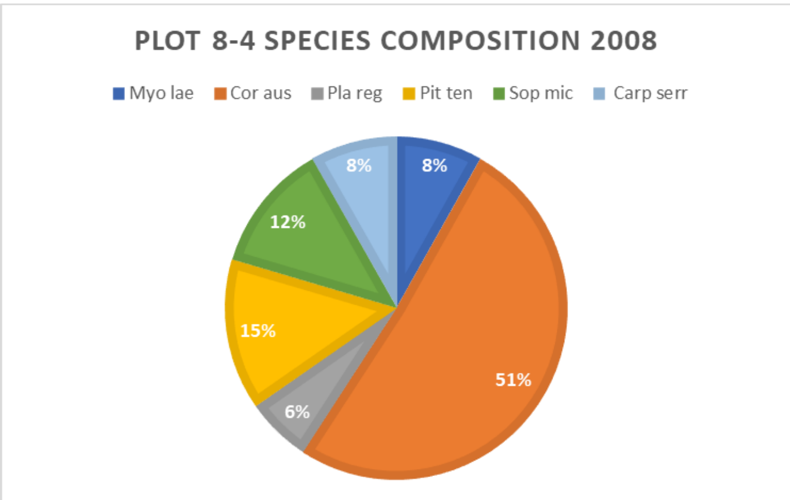

Fig 11: Plot 8-4 species composition at time of planting (2008), percentage of total stocking (4900 SPH).

The resulting plot composition change is notably different for the smaller components, not only through the loss of putaputaweta and addition of new species, but through reductions in proportions of kohuhu and kowhai, and expansion of the Ngaio component (Figure 12).

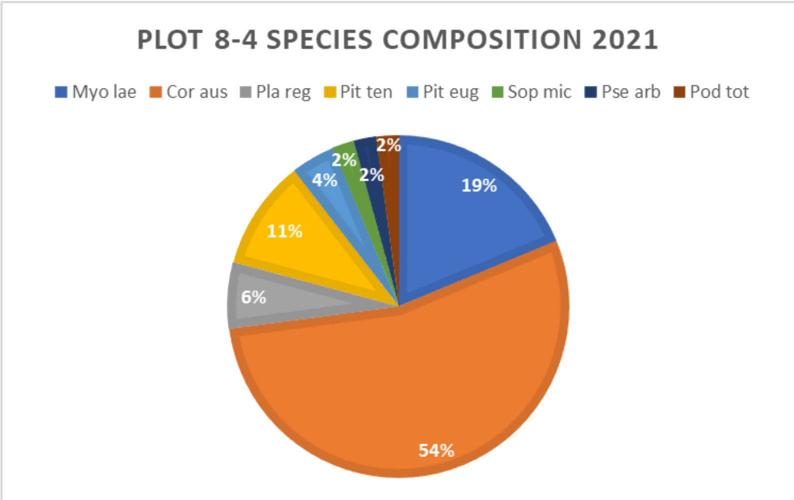

Fig 12: Plot 8-4 species composition at time of sampling (Autumn 2021). Percentage of total stocking (4800 SPH).

A perimeter fence is present on the southern boundary of the site (3 wire plus mesh) but does not appear to have impeded deer (prior to broad deer exclusion from the reserve as a whole) or pigs with biotic damage from both noted on the site, and deer browse of manatu and puahou observed within the plot area.

Drone imagery (Figure 13) shows approximately 64 grid intersections overlapping vegetation which indicates a crown closure of 52.9% (64/121). This site is relatively open with regards to crown closure due to the high proportion of ti kōuka planted. Crown diameter for kohuhu and tarata ranged from 1.5 – 3m, with a mid-point of 2.25m used for carbon calculations. All other species were assessed using either the type 1, 3 or 4 equations given their respective forms.

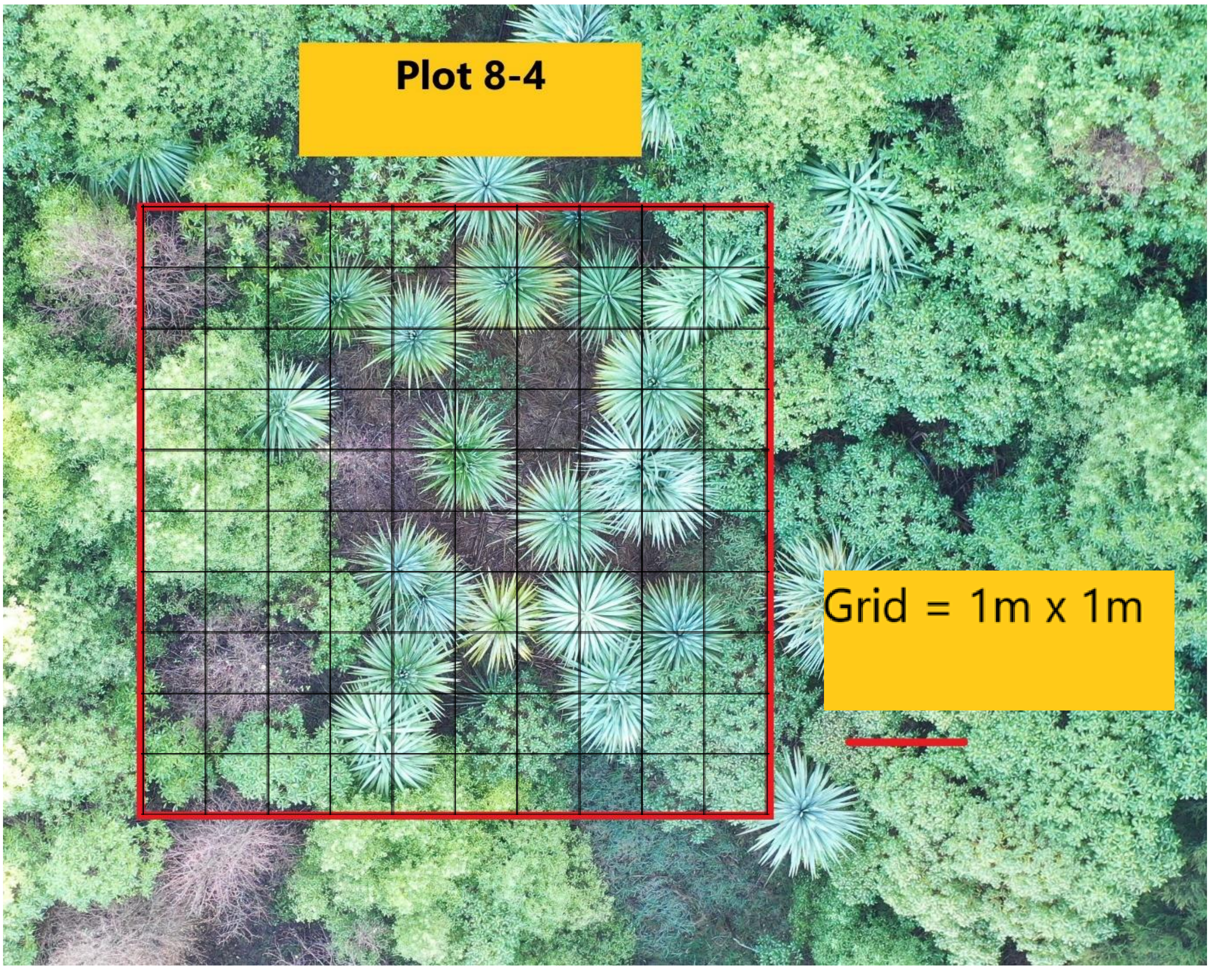

Figure 13: Drone photo of approximate location of Plot 8-4. Note deciduous manatu with limited foliage at time of photo. 1m^2 grid spacing.

Plot 8-5

8-5 had the highest stocking and species diversity of any measured plot, and a dense canopy was resultingly present, shading the understorey. Despite this shade a number of naturally regenerating seedlings of the species in the plot were present reflecting overall health of the site.

Species composition has remained relatively stable since planting for the larger components aside from puahou, with the other total losses being of the minor, putaputaweta, mingimingi, karamu and kaikomako components. Other species present have generally had a similar degree of mortality (where it has occurred) down to the combined current stocking of 4900 SPH (Table 6), which indicates density-induced self-thinning is more likely to be the cause than biotic or abiotic factors. There does not appear to have been any further infill planting into this area, perhaps due to its initial high stocking.

Species	Stocking 2008 – Stems per hectare	Stocking 2021- Stems per hectare	Percentage Change (%)
Tarata (Pit eug)	700	700	*nc*
Puahou (Pse arb)	500	0	-100%
Mikimiki (Cop rot)	500	500	*nc*
Karamū (Cop luc)	700	500	-28.6%
Mingimingi (Cop pro)	100	0	-100%

Karamu (Cop rob)	100	0	-100%
Kapuka (Gri lit)	1800	1300	-27.8%
Makomako (Ari ser)	200	200	*nc*
Kanuka (Kun eri)	800	500	-37.5%
Putaputaweta (Car ser)	200	0	-100%
Horoeka (Pse cra)	100	100	*nc*
Ngaio (Myo lae)	500	500	*nc*
Kohuhu (Pit ten)	400	400	*nc*
Kaikomako (Pen cor)	200	0	-100%
Tī Kōuka (Cor aus)	200	200	*nc*

Table 6: Species composition and stocking change from planting (2008) to present (2021).

The original composition (Figure 14) was diverse and densely stocked, which likely played a factor in its stability given variant crown heights and light competition.

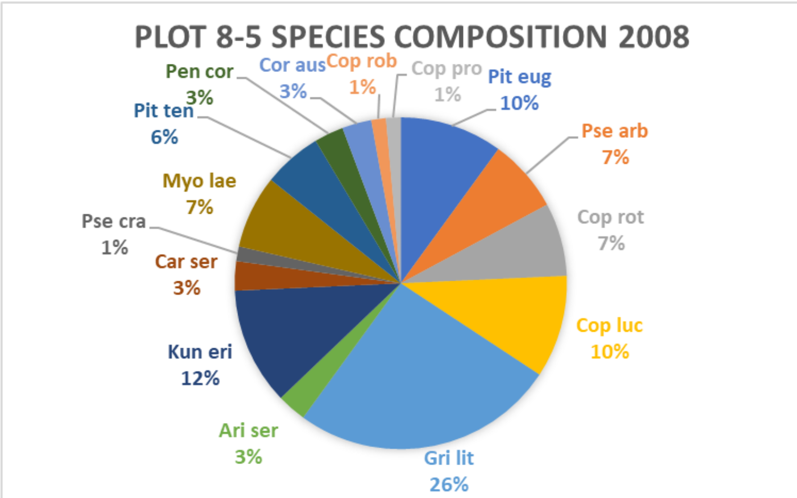

Fig 14: Plot 8-5 species composition at time of planting (2008), percentage of total stocking (7000 SPH).

The composition documented at remeasuring (Figure 15), was however broadly the same for the large components by percentage stocking, and overall stability at this point appears good now that some self-thinning has occurred. This may change over time as larger species continue to grow.

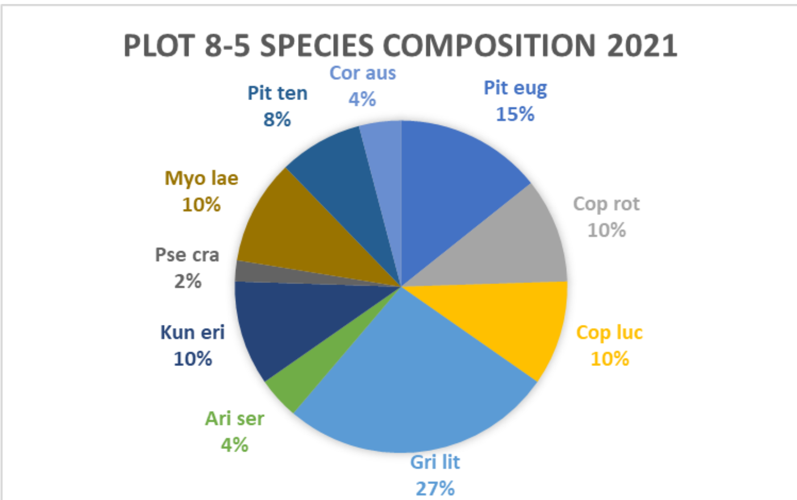

Fig 15: Plot 8-5 species composition at time of sampling (Autumn 2021). Percentage of total stocking (4900 SPH).

The drone photography (Figure 16) outlines the near-total crown closure observed for Plot 8-5 and surrounds. The understory was highly shaded, so this is as expected. The crown closure is estimated to be 85.1%, with 103/121 intersections overlapping vegetation.

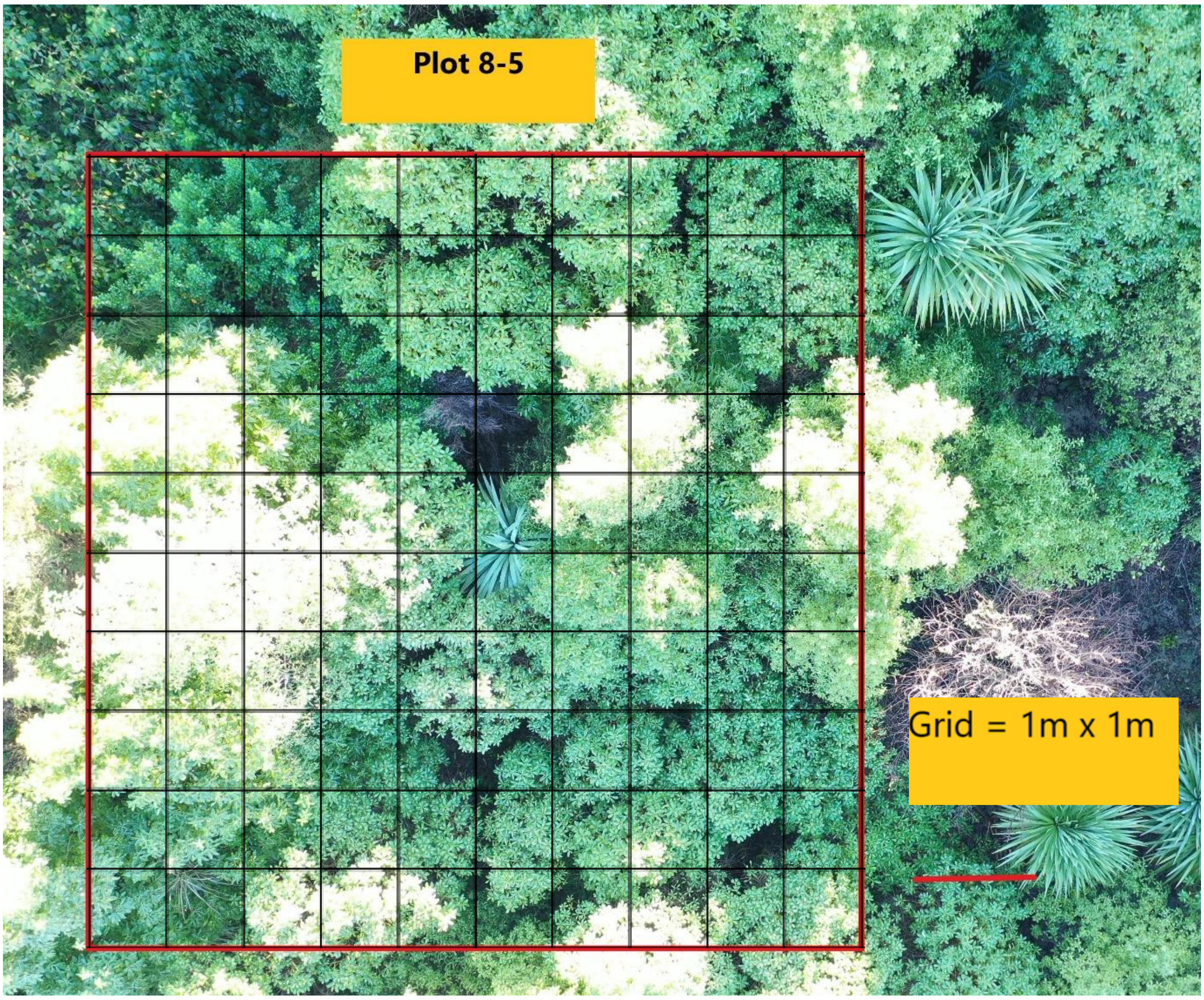

Figure 16: Drone photo of approximate location of Plot 8-5. $1m^2$ grid spacing

Crown diameter is very difficult to assess given the high degree of closure, but compact crowns were generally observed for all species during measurement (given the high level of stocking), and as such indicative values of 2m for kohuhu, kapuka and tarata, and 1.5m for all other species are used in this instance. Type 4 equations were used to estimate the various *Coprosma* species and any species with no measurable DBH.

Growth and Carbon Sequestration

Summary Statistics – Growth

Plot 8-1

Manatu, ti kōuka and ngaio had the greatest height, GLD and DBH periodic increment (PAI) growth for the 13-year period since planting occurred on each of the sites (Table 6). It's notable though that the canopy area of the 2 pittosporums is expanding, and over a longer term they are likely to surpass both manatu and ti kōuka.

2008 Plantings (13-year period) Periodic Annual Increments (PAI): Plot 8-1			
Species	**PAI Height (cm/ann.)**	**PAI GLD (cm/ann.)**	**PAI DBH (cm/ann.)**
Manatu (Pla reg)	55.71	1.35	0.70

Kohuhu (Pit ten)	39.36	1.09	0.40
Ngaio (Myo lae)	56.35	2.23	0.88
Kaikomako (Pen cor)	-	-	-
Kowhai (Sop mic)	41.54	0.48	0.37
Tī kōuka (Cor aus)	35.71	1.39	0.94
Tarata (Pit eug)	49.23	0.67	0.39

Table 6: 13-year Periodic annual increments (PAI) for Height (cm), GLD (cm) and DBH (cm) for Plot 8-1

Plot 8-4

General growth trends were the same (by species) for Plot 8-4 compared to Plot 8-1, (Table 7) with the exception of ngaio which occurred in an unusual uni-stem form at this site despite ample growing space. There was side-shading from the hills on either side and the dense canopy of plot 8-5 nearby, so this may have affected ngaio form/performance. The GLD PAI cannot be assessed for the puahou and totara components which appear to be relatively recent infill plantings judging by size.

2008 Plantings (13-year period) Periodic Annual Increments (PAI): Plot 8-4			
Species	**PAI Height (cm/ann.)**	**PAI GLD (cm/ann.)**	**PAI DBH (cm/ann.)**
Ngaio (Myo lae)	37.18	0.83	0.41
Tī kōuka (Cor aus)	34.17	1.12	0.78
Manatu (Pla reg)	55.90	0.99	0.72
Kohuhu (Pit ten)	37.06	0.70	0.29
Kowhai (Sop mic)	29.23	0.32	0.27
Putaputaweta (Car ser)	-	-	-
Puahou (Pse arb)	-	-	-
Totara (Pod tot)	-	-	-
Tarata (Pit eug)	33.85	0.54	0.24

Table 7: 13-year Periodic annual increments (PAI) for Height (cm), GLD (cm) and DBH (cm) for Plot 8-4

Plot 8-5

This plot (and surrounds) comprised several transplanted seedlings/saplings rescued from the sub-canopy of remnant “A”, and as such GLD growth cannot be estimated without being able to differentiate between planted and transplanted species. Height (using original averages on PSP establishment) and DBH (where applicable) can be however (Table 8). Growth rates for height slightly exceeded the other two 2008 Plantings reflecting the dense stocking/high canopy closure influencing height growth for light competition. The plantings were all healthy in appearances and several seedlings were observed indicating the success of the site in fostering natural regeneration.

2008 Plantings (13-year period) Periodic Annual Increments (PAI): Plot 8-5			
Species	**PAI Height (cm/ann.)**	**PAI GLD (cm/ann.)**	**PAI DBH (cm/ann.)**
Kohuhu (Pit eug)	51.10	*	0.48
Puahou (Pse arb)	-	*	-
Mikimiki (Cop rot)	27.23	*	0.23
Karamū (Cop luc)	35.85	*	0.27
Mingimingi (Cop pro)	-	*	-

Karamu (Cop rob)	-	*	-
Kapuka (Gri lit)	26.51	*	0.23
Makomako (Ari ser)	51.92	*	0.67
Kanuka (Kun eri)	52.31	*	0.39
Putaputaweta (Car ser)	-	*	-
Horoeka (Pse cra)	45.38	*	0.31
Ngaio (Myo lae)	56.62	*	0.81
Kohuhu (Pit ten)	39.00	*	0.36
Kaikomako (Pen cor)	-	*	-
Tī Kōuka (Cor aus)	44.62	*	0.80

Table 8: 13-year Periodic annual increments (PAI) for Height (cm), GLD (cm) and DBH (cm) for Plot 8-5

Comparing the height measurement ranges (Figure 17) by species for each of the three 2008 plantings at each time they were remeasured (2008, 2010, 2021) shows that despite wide height ranges being observed within and between sites, the ranges overlap where the same species were observed at multiple sites. This suggests common height growth performance for the 2008 Plantings despite site and stocking variation once mortality had reduced some sites down to a more optimum stocking.

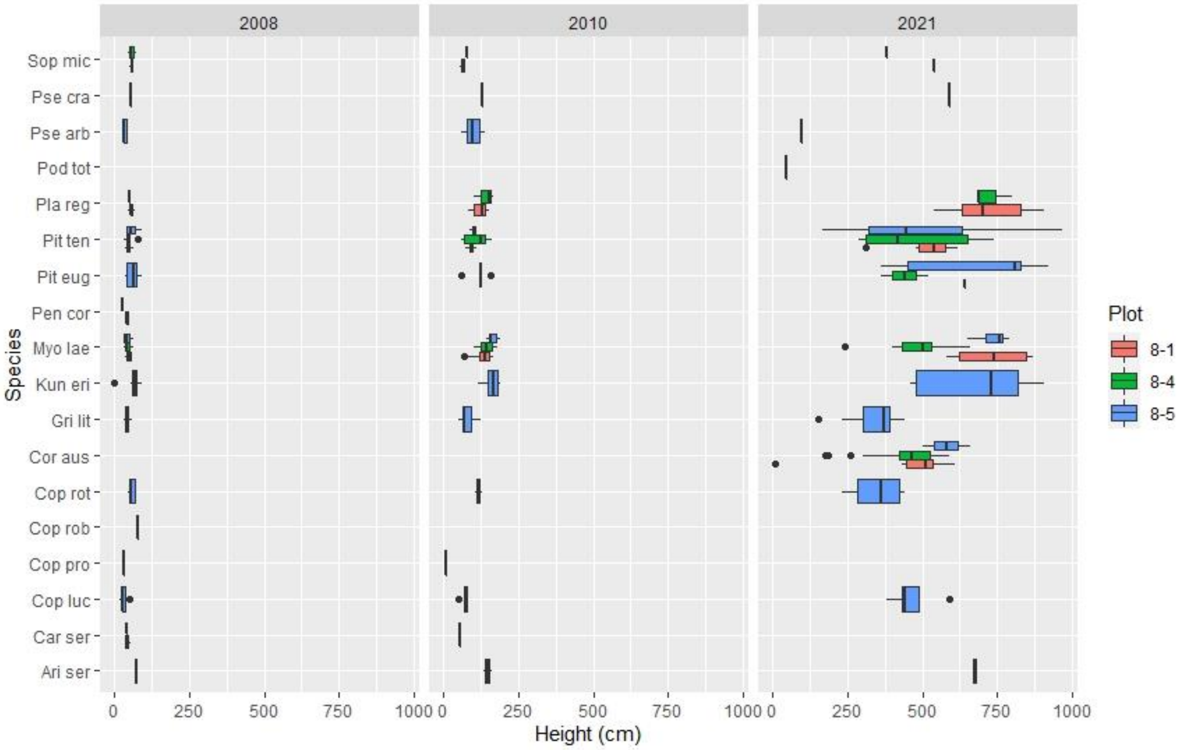

Figure 17: Height vs Species by Plot/Measurement year boxplots for all 2008 Plantings.

The aggregated 2008 height growth scatterplots (Figure 18) by species shows a general trend (LOESS line regressions) for all species towards plateauing of height growth at different degrees. It is likely the canopy will increase at a slower rate for some years, but is approaching a stable maximum at this level of stocking for the majority of species planted. It is possible that some of the species with higher maximum heights (eg: totara, kowhai, or ribbonwood) may experience a second surge in growth once other species approach their height maximum and then suppress those species to a degree.

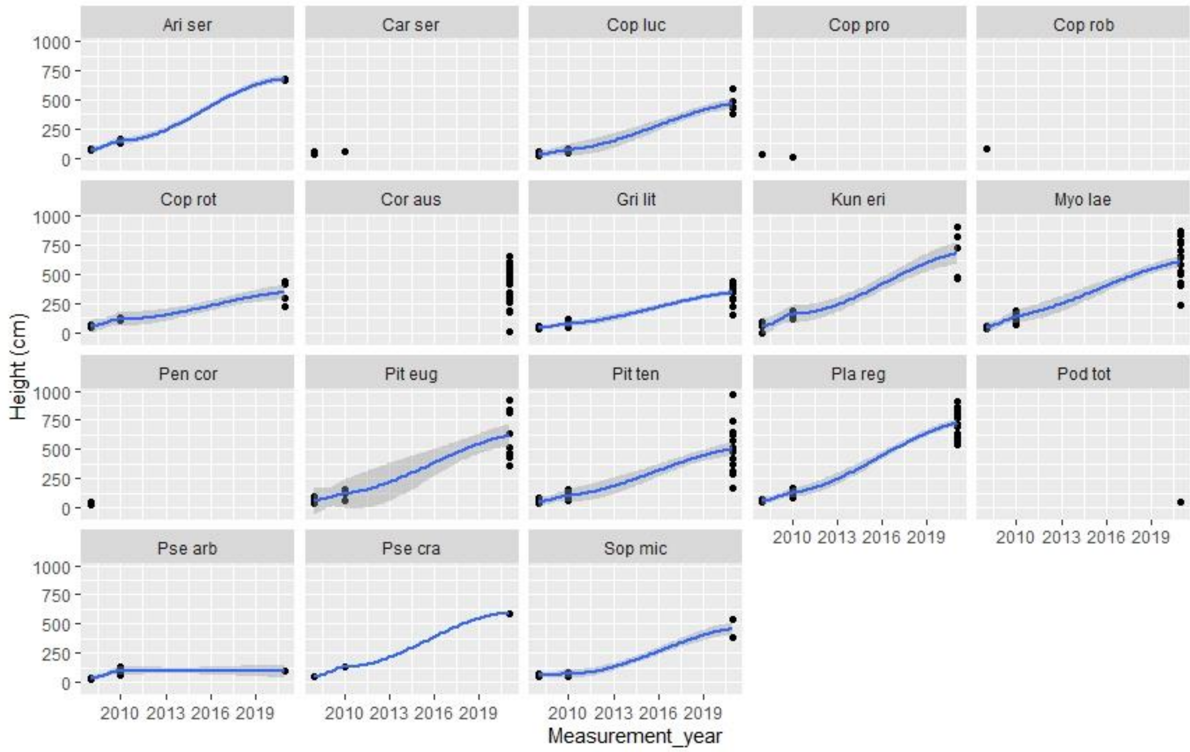

Figure 18: Aggregated 2008 Planting height growth scatterplots (Species vs Measurement year) with LOESS regression lines and CL bands.

The aggregated GLDs by species for the 2008 plantings (Figure 19) show similar overlap in measured ranges, despite wide ranges. A sole exception is for ngaio at the site represented by plot 8-1, with ngaio on this site being substantial in horizontal and branch size and this requiring proportionately large GLD. This is likely a site-specific effect due to abiotic factors (aspect, soil moisture etc).

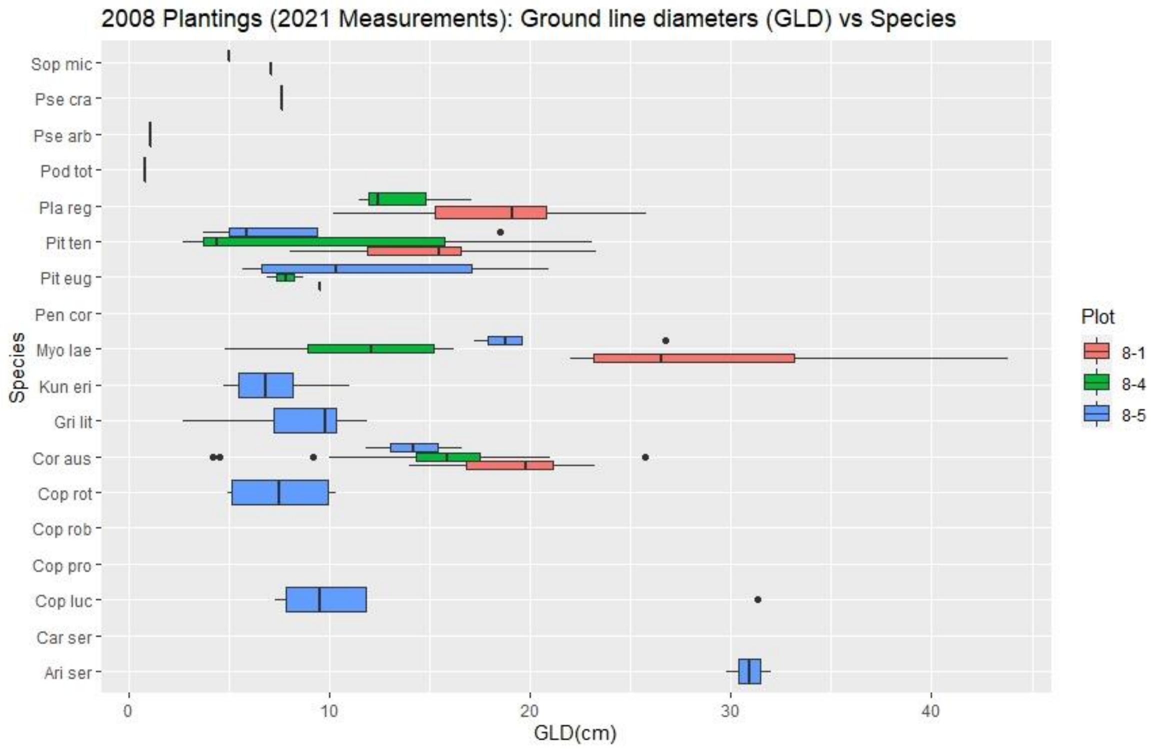

Figure 19: GLD (cm) vs Species by Plot for all 2008 Plantings as at 2021.

The combined DBH measurements of species vs plot as at 2021 (Figure 20) showed more consistent overlap of measured values versus ranges than the GLDs. Taken together, the 3 growth metrics show consistent (comparable ranges) growth of all species between the 3 sites over the 13 year period since planting, where mortality has not occurred.

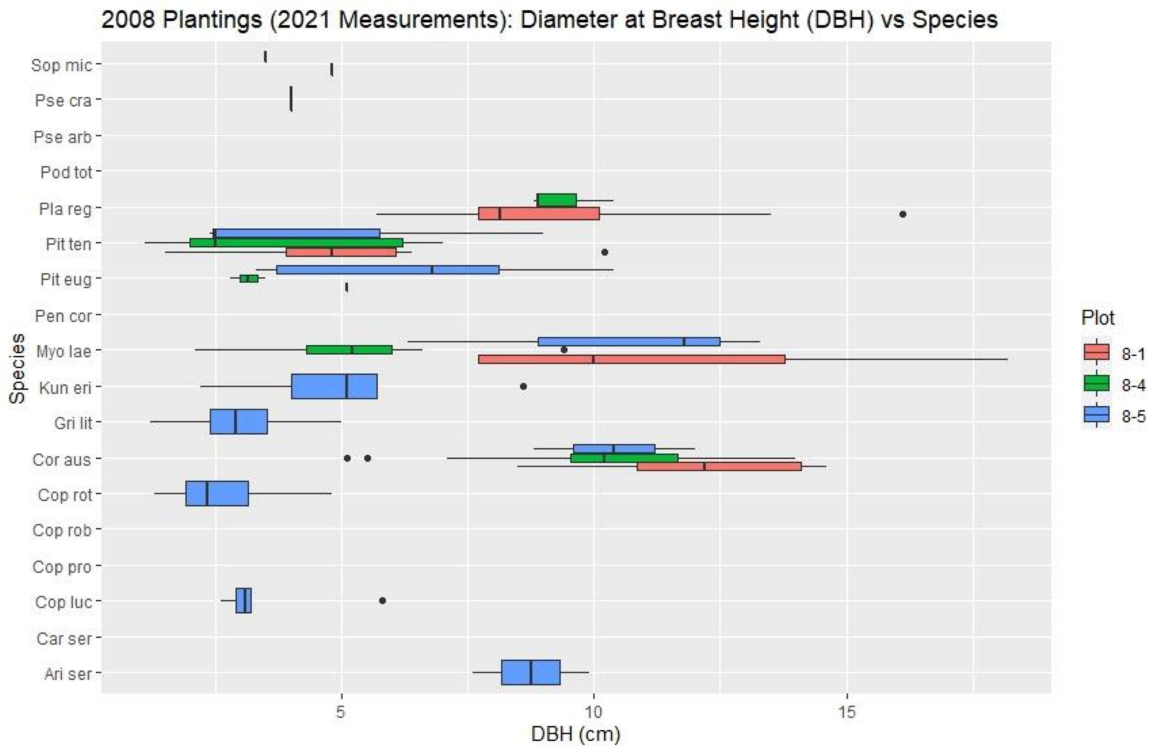

Figure 20: DBH (cm) vs Species by Plot for all 2008 Plantings as at 2021.

Summary statistics – Carbon

The combined carbon sequestration calculated for the 2008 plantings (Table 9) may overestimate the total by 30% or more due to the influence of a small number of ngaio with very large GLDs[6] and the resulting impact of that of the AGB/BGB calculated for those examples. This influence will become less distorting (ie: more accurate) as the ngaio mature and the GLD's better represent the actual size of the ngaio biomass. Overall, the per hectare rate of CO_2 sequestration exceeded that of the 2006 plantings by a factor of 2, although as mentioned above: ngaio may have skewed the result. Of the species other than ngaio and karamu (which being a shrub is harder to quantify accurately), kohuhu, tarata and manatu had the greatest degree of individual carbon stored per average stem.

Combined Carbon Estimates – All 2008 Plantings					
Species	**Average AGB + BGB per Stem (kg est.)**	**Average Carbon per Stem (kg est.)**	**# Stems**	**CO_2 stored (tonnes/Combined Plot area)**	**CO_2 stored per hectare (tonnes per hectare est.)**
Tarata (Pit eug)	20.47	10.23	10	0.38	12.5
Manatu (Pla reg)	20.05	10.03	17	0.62	20.7
Puahou (Pse arb)	0.31	0.16	1	0.0006	0.019
Mikimiki (Cop rot)	5.63	2.82	4	0.04	1.3
Karamū (Cop luc)	26.39	13.20	5	0.07	2.2
Mingimingi (Cop pro)	-	-	-	-	-
Karamu (Cop rob)	-	-	-	-	-
Kapuka (Gri lit)	11.11	5.56	13	0.26	8.8
Makomako (Ari ser)	9.10	4.55	2	0.03	1.1
Kanuka (Kun eri)	9.53	4.77	5	0.09	2.9
Putaputaweta (Car ser)	-	-	-	-	-
Horoeka (Pse cra)	0.73	0.36	1	0.0053	0.178
Ngaio (Myo lae)	100.83	50.41	18	3.33	110.9
Kohuhu (Pit ten)	23.46	11.73	15	0.65	21.5
Kaikomako (Pen cor)	-	-	-	-	-
Tī Kōuka (Cor aus)	16.81	8.40	39	1.20	40.1
Kowhai (Sop mic)	2.64	1.32	2	0.01	0.3
Totara (Pod tot)	0.19	0.1	1	0.0004	0.012
Total (Sum):	**247.15**	**123.58**	**133**	**6.69**	**222.50**

Table 9: Average Above Ground/Below Ground biomass (kg) stored per stem, and total CO_2 sequestered by species for all 2008 Plots and per Hectare.

[6] The AGB equation used for ngaio uses only GLD as a variable given the irregular tree form it models, so large GLDs on young stems may lead to over-estimation.

2011 Plantings

Stocking and Composition

Plot 11-1 is 112m^2 (8m x 14m), although listed in earlier documents as being 126m^2 (9 x 14m), and is located at the valley bottom on flat, grassy terrain. Initial stocking was high at around 4400 SPH, with kahikatea (*Dacrycarpus dacrioides*) forming the most numerous planting, followed by roughly equivalent numbers of manatu, tī kōuka, and manuka (*Leptospermum scoparium*). Grass in the area is high (~0.6m average) and chemical spot preparation prior to planting and/or weed matting after planting, would have occurred as per the Restoration Plan (Norton 2005).

Plot 11-3 is 96m^2 (8m x 12m) and represents a wet (high-standing water) toe-slope area planted in manatu and Matai (*Prumnopitys taxifolia*), with a minor manuka (*Leptospermum scoparium*), tī kōuka, kowhai and kapuka components. Initial stocking was high at around 3850 SPH with the majority of plantings being Manatu (48%) and matai (27%), followed by the smaller components of kapuka, kowhai, manuka, and tī kōuka.

Plot 11-4 is an irregular shaped 91m^2 plot (13m x 6m x 13m x 8m) located on the upper slope of a north aspect site with a site slope of 25% within the PSP. The Plot's eastern boundary was a fence line which may have impacted animal behaviour in the plot and surrounding area, but as a low wire fence is unlikely to have impeded either deer or pigs. Initial stocking was 4175.8 SPH, this being primarily kanuka (42%) and roughly equivalent proportions of kohuhu (18%), tarata (16%) and totara (*Podocarpus totara* – 13%) followed by minor components of kowhai, manatu and matai.

Plot 11-1

The stocking of the plot and surrounds has more than halved from 4444 SPH to 1904 SPH (Table 10). This trend was visible across all plantings in the valley bottom of Tiromoana but had greatest impact on podocarps and manuka. Animal damage (historic and current) was observed on a majority of the manatu, but they appeared otherwise unimpacted.

Species	Stocking 2011 – Stems per hectare	Stocking 2021- Stems per hectare	Percentage Change (%)
Kahikatea (Dac dac)	1746.0	79.4	-95.5%
Manuka (Lep sco)	634.9	0	-100%
Manatu (Pla reg)	873.0	793.7	-9.1%
Tī kōuka (Cor aus)	1190.5	1031.7	-13.3%

Table 10: Species composition and stocking change from planting (2011) to present (2021).

The original plot composition comprised roughly equivalent proportions of manuka and manatu, and larger proportions of ti kouka and kahikatea, the latter comprising 39% of plantings by number (Figure 21)

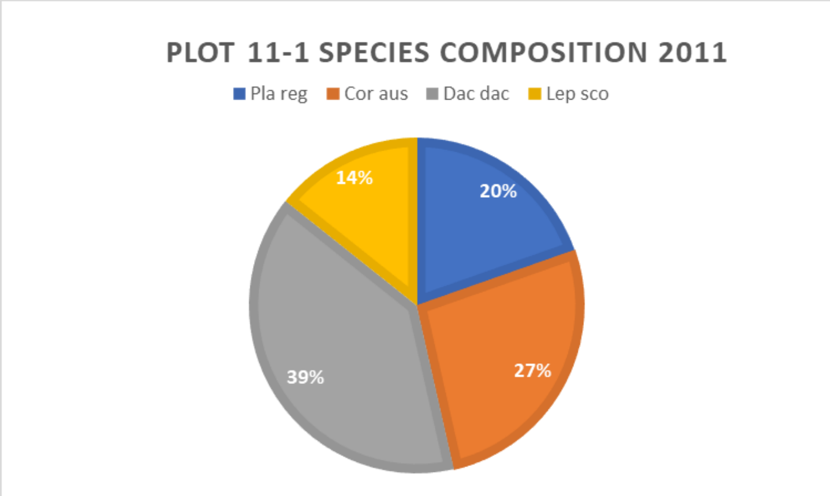

Fig 21: Plot 11-1 species composition at time of planting (2011), percentage of total stocking (4444 SPH).

The species composition of the plot has, however, shifted considerably in the intervening 10 years (Figure 22), with total, or near-total, mortality of the manuka and kahikatea plantings respectively. The Tī kōuka and Manatu plantings conversely have had similarly low mortality over the 10 year period, and despite substantial deer rubbing damage being noted to the Manatu, this does not appear to have impacted it's overall mortality although it may have had an impact on growth.

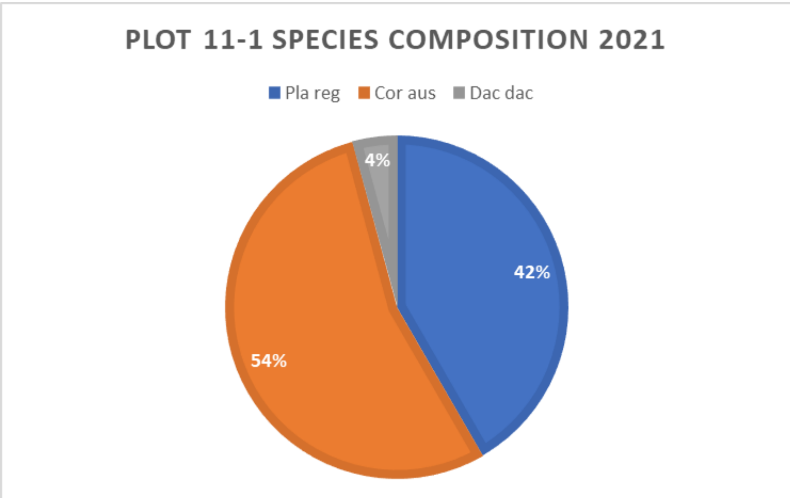

Fig 22: Plot 11-1 species composition at time of sampling (Autumn 2021). Percentage of total stocking (1904.8 SPH).

The aerial drone photography clearly shows the open canopy (very low crown closure) reflective of both the high mortality that has occurred at the site and the compact crowns of the selected species. It is also difficult to calculate given the deciduous manatu being free of foliage at time of photography giving it the appearance of being far more open than it actually is. 66/135 grid intersection (or estimated equivalent) are contacting vegetation, giving an estimated crown closure of 48.9%. Crown diameters are estimated as being 1.5m for ti kōuka and 1m for manatu.

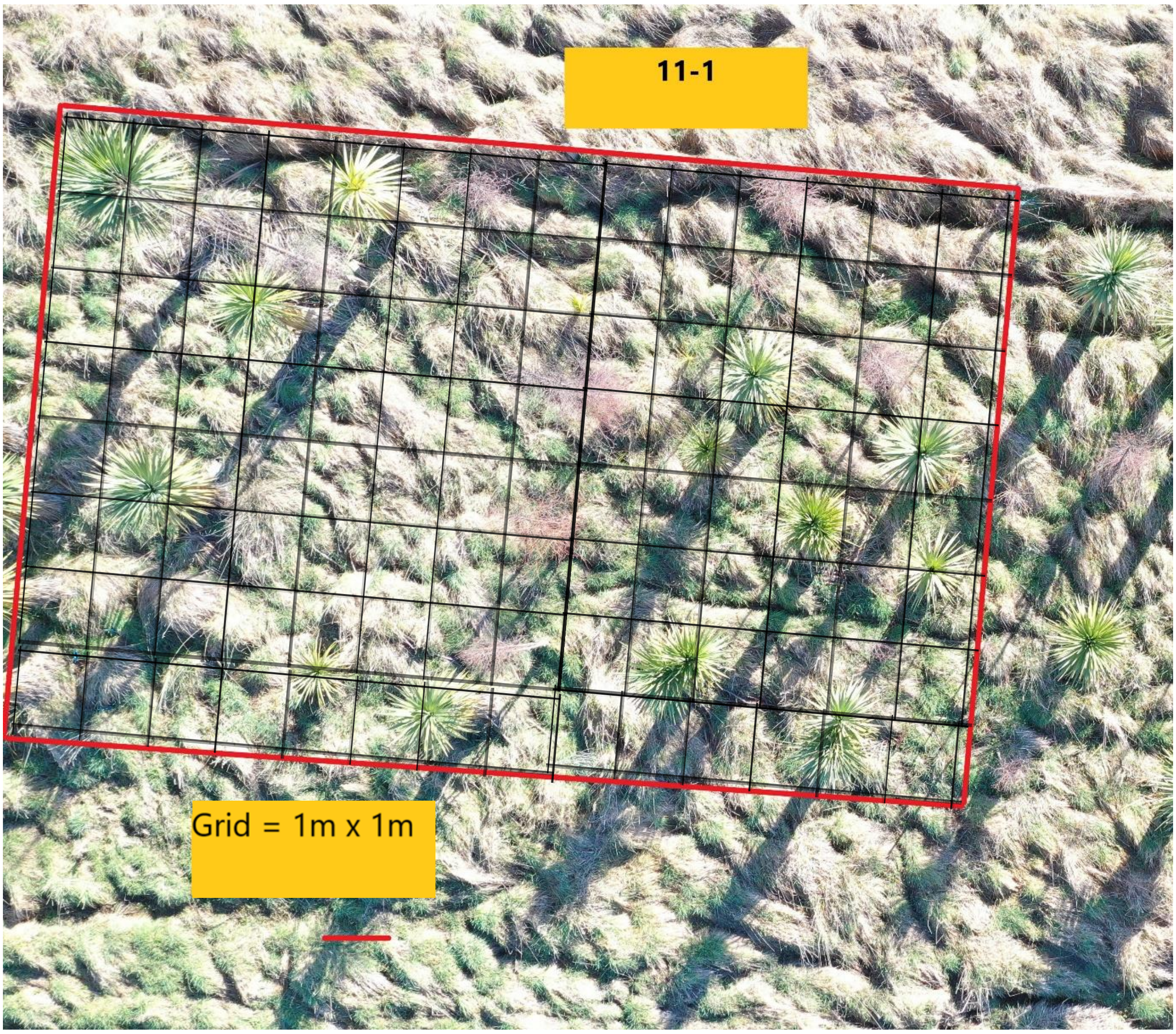

Figure 23: Drone photo of approximate location of Plot 11-1. 14m x 8 m plot (112m^2), 1m^2 grid spacing. Note deciduous manatu are difficult to identify.

Plot 11-3

Present stocking is at roughly half (1979 SPH) the initial rate but with notably higher mortality of the matai component comprising most of the reduction in stock, along with total loss of the smaller manuka and kapuka component within the PSP (Table 11). The toe-slope area plot 11-3 is located within also had high seedling mortality and substantial animal damage noted along with fresh pig rooting and pigs seen onsite (at time of measurement). The broader toe-slope area had greatest stock numbers amongst manatu and ti kōuka, with patches of manuka and scattered kowhai also noted. No significant numbers of kapuka or matai were identified in the broader area.

Species	Stocking 2011 – Stems per hectare	Stocking 2021- Stems per hectare	Percentage Change (%)
Manatu (Pla reg)	1875	1354.2	-27.8%
Matai (Pru tax)	1041.7	104.2	-90%
Kowhai (Sop mic)	104.2	104.2	*nc*
Kapuka (Gri lit)	104.2	0	-100%
Manuka (Lep sco)	312.5	0	-100%
Tī kōuka (Cor aus)	416.7	416.7	*nc*

Table 11: Species composition and stocking change from planting (2011) to present (2021).

The original plot composition shows the significant (27%) component of matai (Figure 24), in relation to the other minor components, and main component of manatu.

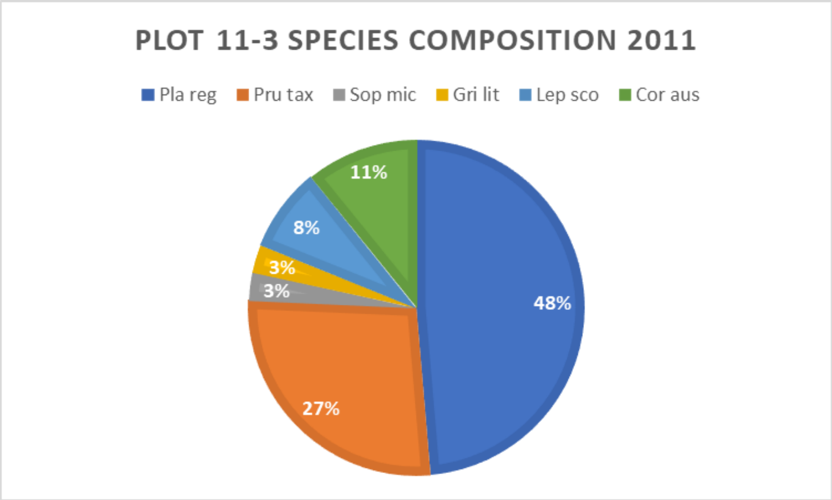

Fig 24: Plot 11-3 Species composition at time of planting (2011) Percentage of total stocking (3854.2 SPH)

By time of measurement the matai component is minimal, and kapuka and manuka absent entirely, although the manatu, ti kōuka, and kowhai have remained relatively unchanged with regards to numbers (Figure 25).

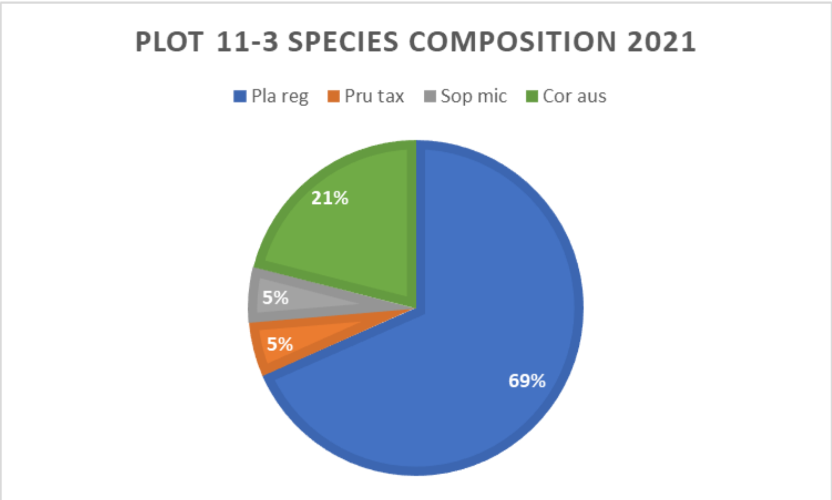

Fig 25: Plot 11-3 Species composition at time of sampling (Autumn 2021). Percentage of total stocking (1979.2 SPH)

The aerial imagery is, similarly to plot 11-1, difficult to assess for crown closure with the manatu being absent of foliage. However, an estimated 73/117 grid intersections contact vegetation given a crown closure of 62.4%. Crown diameters for carbon equations are estimated at 1m for manatu and 1.5m for ti kouka respectively, with a surrogate value of 0.5m used for matai (Type 4 equation).

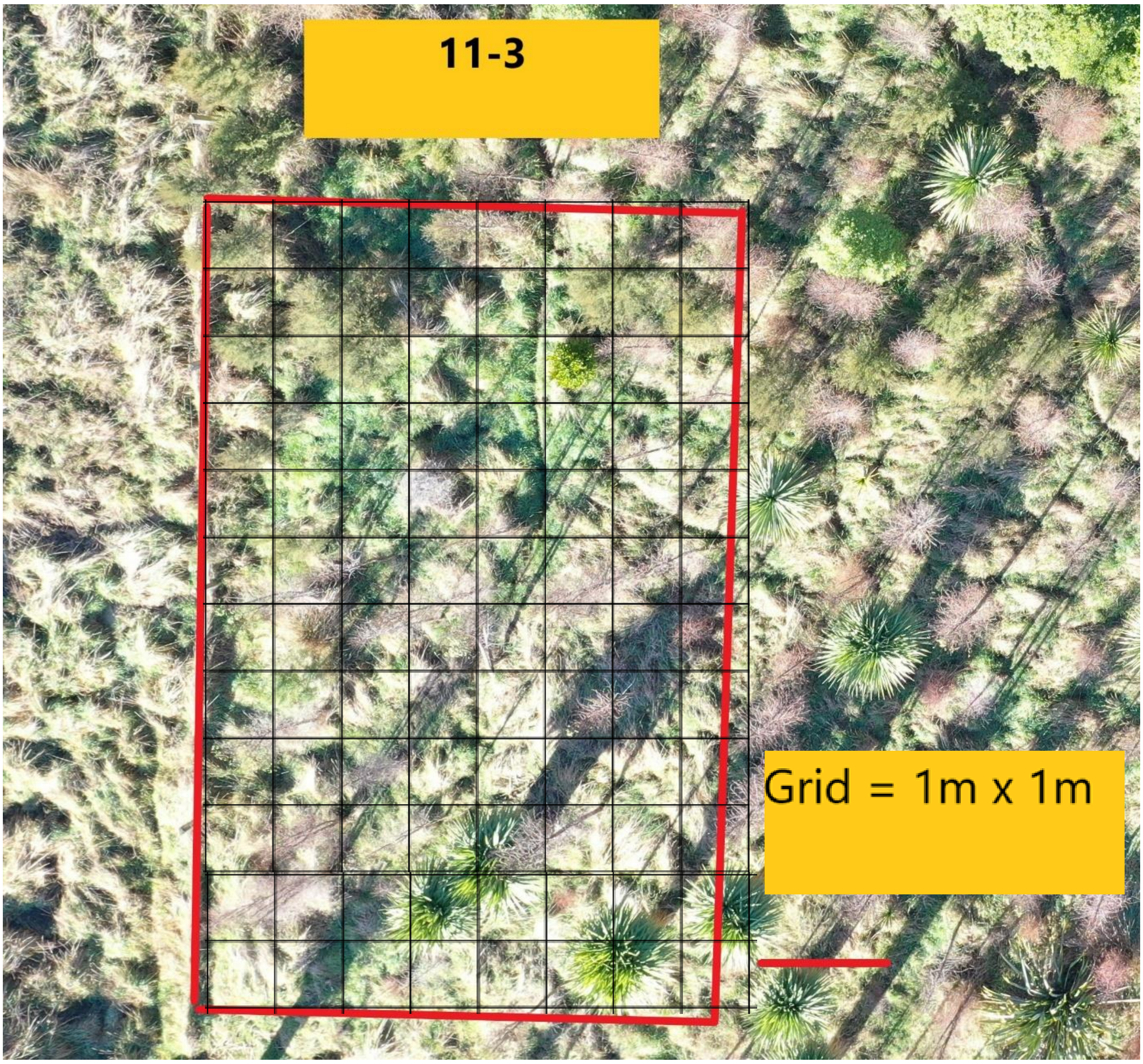

Figure 26: Drone photo of approximate location of Plot 11-3. 12m x 8 m plot (96m^2), 1m^2 grid spacing. Note deciduous manatu are difficult to identify.

Plot 11-4

Initial stocking was high at 4175.8 SPH, however mortality on this site has not been as extreme as for the other 2011 plantings except for the minor species components, with present stocking also persisting at a high level (3406.6 SPH) and with nearly full closure of canopy having occurred (Table 12) Overall species composition remains stable between plantings and sampling except for the omission of the 2 most minor species components (manatu and matai), which are absent, however it cannot be assessed whether this was due to animal browse/damage or inter-species growth competition without any clear evidence.

Very minimal animal damage was noted which may be a reflection of the dense nature of the planting discouraging movement through it to a degree, but there was indication of some recent low-level deer sign in the vicinity, which indicates a small scale breach somewhere in the perimeter deer fence. The incidence was sufficiently low to indicate that perhaps only 1-2 deer have breached the fenced area.

Species	Stocking 2011 – Stems per hectare	Stocking 2021- Stems per hectare	Percentage Change (%)
Kanuka (Kun eri)	1758.2	1318.7	-25%
Totara (Pod tot)	549.5	439.6	-20%
Kowhai (Sop mic)	219.8	219.8	*nc*
Kohuhu (Pit ten)	769.2	879.1	+14.3%
Tarata (Pit eug	659.3	549.5	-16.7%
Manatu (Pla reg)	109.9	0	-100%
Matai (Pru tax	109.9	0	-100%

Table 12: Species composition and stocking change from planting (2011) to present (2021).

This PSP has minimal compositional change (Compare: Figures 27 & 28) since it's planting other than total mortality of the minor matai (*Prumnopitys taxifolia*) and manatu component. Minimal mortality was observed for the kanuka and totara (*Podocarpus totara*) at 25% and 20% respectively, and none for the small kowhai component.

There may have been a transcribing error in the original PSP measurements, as while a single planted tarata (*Pittosporum eugenoides*) was absent during remeasurement and recorded as a mortality, an additional kohuhu (*Pittosporum tenuifolium*) was definitively identified within the PSPs area and accounts for the variation between the 2 species precisely. If a transcribing error did occur, then no mortality has occurred for either tarata of kohuhu during the intervening period since planting.

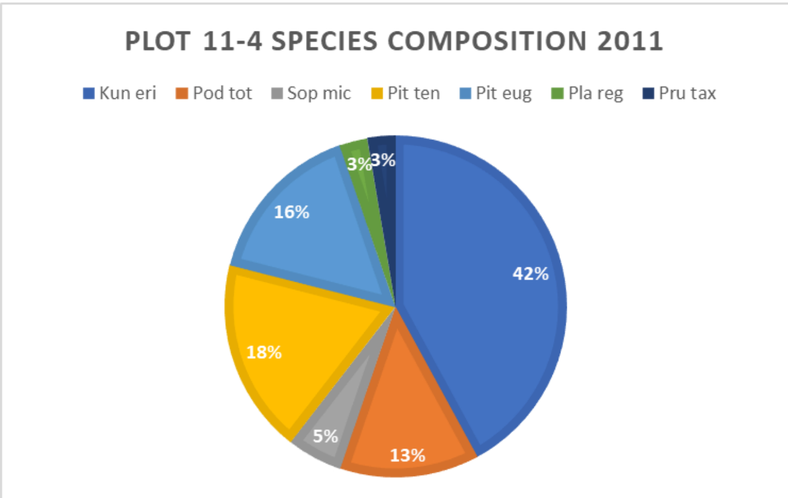

Fig 27: Plot 11-4 Species composition at time of planting (2011) Percentage of total stocking (4175.8 SPH)

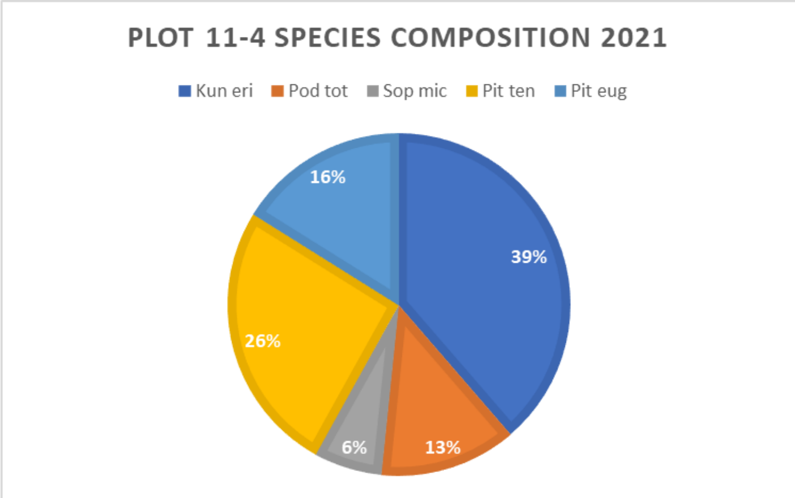

Fig 28: Plot 11-4 Species composition at time of sampling (Autumn 2021). Percentage of total stocking (3406.6 SPH)

Overall, the mid-slope and upper-slope sites showed vigorous growth and tight canopy closure and resemble a natural successional forest. Regeneration was not observed within the PSP but was noted in the vicinity with a small number of kohuhu seedlings and kanuka seedlings observed. This indicates that a natural regeneration cycle may be sustainable in the planted area in the longer term.

The drone photography confirmed the ground findings of tight canopy closure, with 84/107 (approximate) grid intersections contacting vegetation, giving a crown closure of 78.5%. It should be noted this phot had to be taken at high altitude (50m) than other sites given terrain issues, and this may affect estimation of crown closure. Crown diameters are estimated as 2.5m for tarata, 1.5m for kohuhu, 1m for kanuka and 0.5m for totara.

Figure 28: Drone photo of approximate location of Plot 11-4. 13m x 6 m x 8m plot ($91m^2$), $1m^2$ grid spacing approximately. Note ti kōuka bottom right was uprooted and not counted as dead/dying.

Growth and Carbon Sequestration

Summary Statistics – Growth

Plot 11-1

The 10-year periodic growth rates for the 2011 plantings were quite variable between the 3 sites, with the valley bottom planting (11-1) having lower growth across all categories (Table 13) for similar species (manatu and ti kōuka) occurring on the nearby toe-slope planting (11-3). This may reflect biotic and abiotic constraints of the site (vegetation competition, frost, animal damage etc)

2011 Plantings (10-year period) Periodic Annual Increments (PAI): Plot 11-1			
Species	PAI Height (cm/ann.)	PAI GLD (cm/ann.)	PAI DBH (cm/ann.)
Kahikatea (Dac dac)	12.30	0.03	-
Manuka (Lep sco)	-	-	-
Manatu (Pla reg)	40.50	0.64	0.39
Tī kōuka (Cor aus)	24.51	1.32	0.90

Table 13: 10-year periodic annual increment (cm) vs species for plot 11-1

Plot 11-3

Similarly, the toe-slope planting (plot 11-3) had lower PAI rates (Table 14) for the one species it shared in common (kowhai) with the upper slope planting (plot 11-4). Being subject to similar constraints to plot 11-1 but being more densely stocked and more sheltered so having greater observed growth than 11-1.

2011 Plantings (10-year period) Periodic Annual Increments (PAI): Plot 11-3			
Species	PAI Height (cm/ann.)	PAI GLD (cm/ann.)	PAI DBH (cm/ann.)
Manatu (Pla reg)	45.54	0.84	0.59
Matai (Pru tax)	9.60	0.07	-
Kowhai (Sop mic)	33.00	0.62	0.37
Kapuka (Gri lit)	-	-	-
Manuka (Lep sco)	-	-	-
Tī kōuka (Cor aus)	36.43	2.07	1.36

Table 14: 10-year periodic annual increment (cm) vs species for plot 11-3

Plot 11-4

The upper-slope planting (plot 11-4) had vigorous growth of all species (Table 15) present except an uprooted ti kōuka (not recorded), and appeared to be an optimal site for the species mix planted.

2011 Plantings (10-year period) Periodic Annual Increments (PAI): Plot 11-4			
Species	PAI Height (cm/ann.)	PAI GLD (cm/ann.)	PAI DBH (cm/ann.)
Kanuka (Kun eri)	42.92	0.71	0.46
Totara (Pod tot)	29.00	0.46	0.26
Kowhai (Sop mic)	44.00	0.79	0.54
Kohuhu (Pit ten)	44.88	1.16	0.51
Tarata (Pit eug	46.02	1.14	0.40
Manatu (Pla reg)	-	-	-
Matai (Pru tax	-	-	-

Table 15: 10-year periodic annual increment (cm) vs species for plot 11-4

The combined height growth versus measurement year/plot boxplots (Figure 29) shows overlapping ranges at least through to the data tails (which each comprise 2.5% of data range), which indicates comparable height growth for the same species on each of the sites within those ranges (outliers not withstanding).

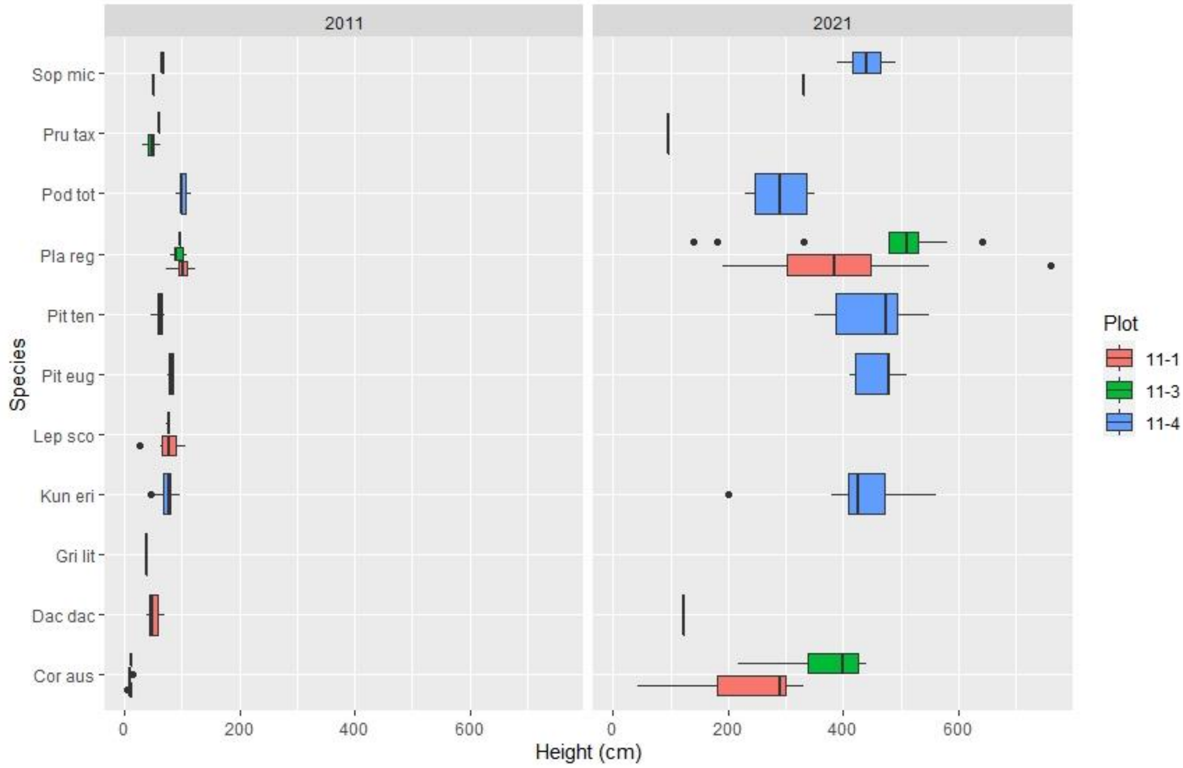

Figure 29: Height vs Species by Plot/Measurement year boxplots for all 2011 Plantings.

Combined 2011 Height growth vs measurement year/species scatterplots (Figure 30) seem to show a plateauing of height growth for all species (LOESS regression lines), indicating maximum canopy height may have almost been achieved for most species, however this is more likely due to there only being two measurement dates captured to model, with growth pattern unknown. The podocarp species (matai, totara, kahikatea) in particular, are likely to experience an accelerating growth trend over a longer time period despite any present slowing, given their known mature height range.

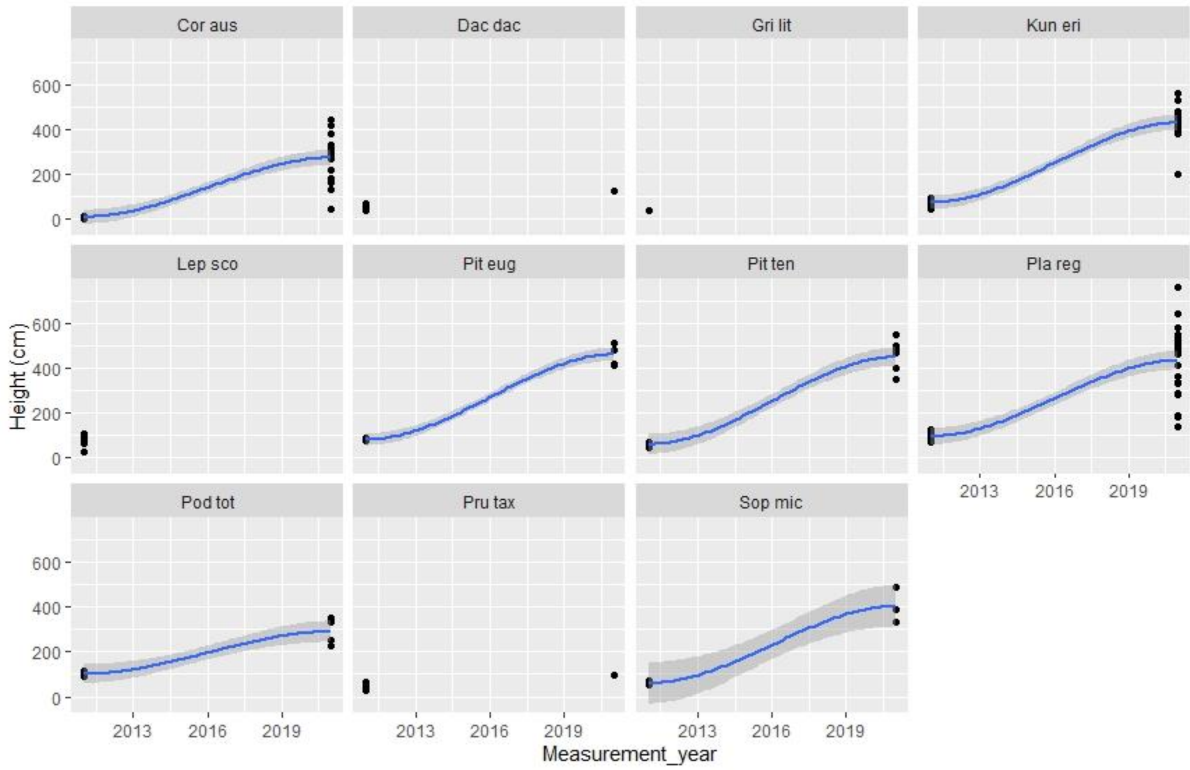

Figure 30: Height growth vs Species/Measurement year scatterplots for combined 2011Plantings. With LOESS lines and CL bands.

GLD versus species/plot boxplots (Figure 31) show generally overlapping (at least at data tails) ranges for GLDs measured in 2021, indicating similar growth across sites once established. DBH versus species/plot boxplots (Figure 32) have the same trend except for ti kōuka, but that may reflect the site species constraints of the 2 plots it was present surviving on (11-1 and 11-3).

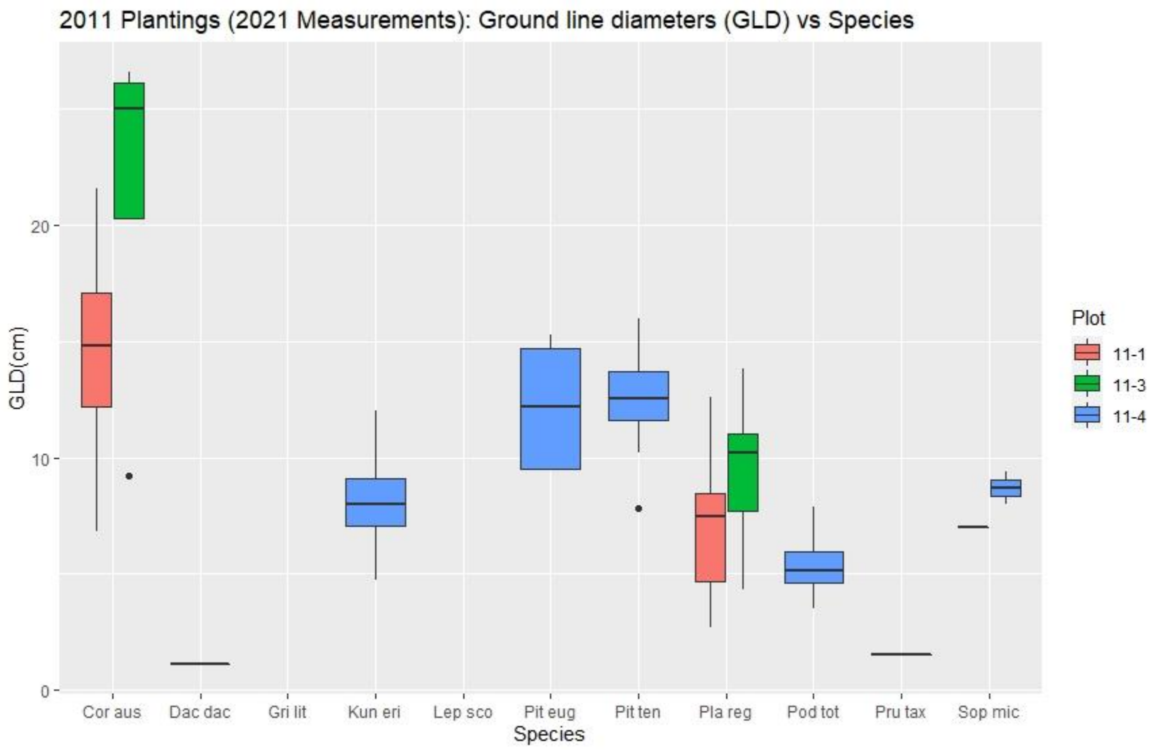

Figure 31: GLD vs Species/Plot as at 2021 for 2011 plantings.

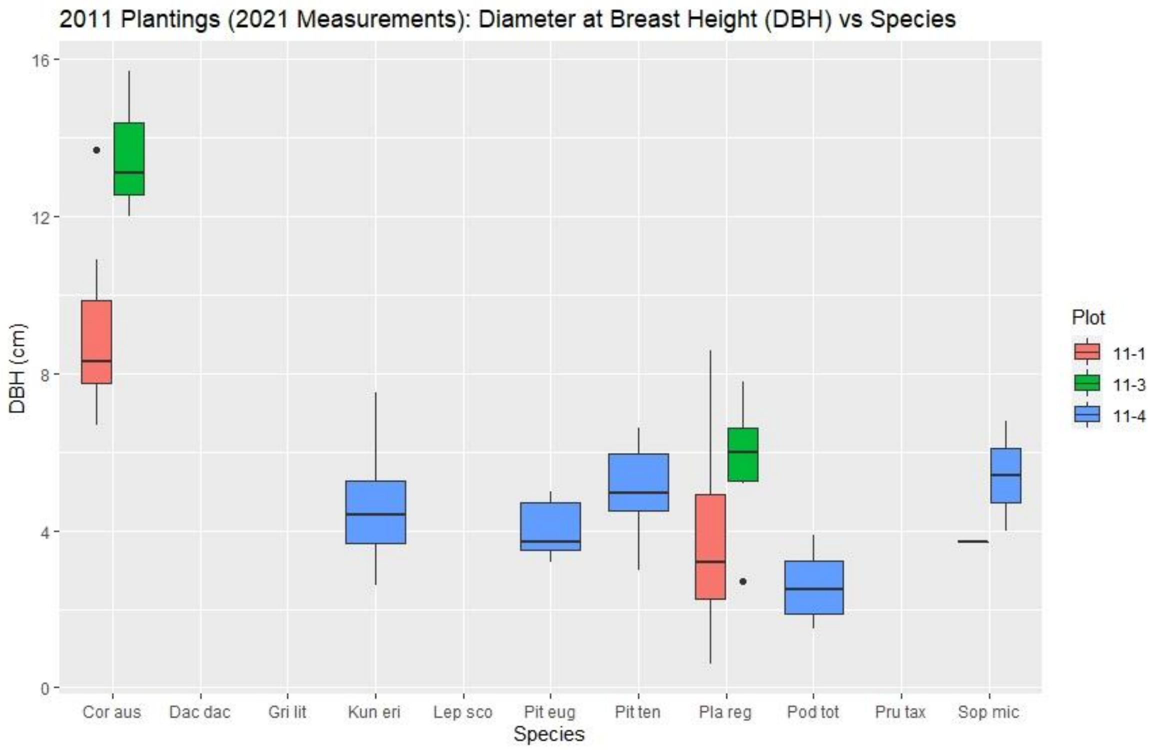

Figure 32: DBH vs Species/Plot as at 2021 for 2011 plantings.

Summary statistics- Carbon

The total carbon (CO2) sequestered per hectare by the 2011 plantings (Table 16) was substantially lower than the other earlier plantings (2006 and 2008) but this is not surprising given both the younger age of the planting and the lower comparative stocking – particularly for the valley bottom (Plot 11-1) and Toes-slope (Plot 11-3) plantings, which had high mortality and had surviving species with predominantly uni-stem form with compact crowns. Tarata is an exception, being only found in the upper-slope planting area (Plot 11-4) and having a much larger average crown diameter than other species in that area.

Combined Carbon Estimates – All 2011 Plantings					
Species	**Average AGB + BGB per Stem (kg est.)**	**Average Carbon per Stem (kg est.)**	**# Stems**	**CO_2 stored (tonnes/Combined Plot area)**	**CO_2 stored per hectare (tonnes per hectare est.)**
Kanuka (Kun eri)	6.35	3.17	12	0.14	4.67
Totara (Pod tot)	0.78	0.39	4	0.0057	0.1903
Kowhai (Sop mic)	5.52	2.76	3	0.03	1.02
Kohuhu (Pit ten)	2.07	1.04	8	0.03	1.02
Tarata (Pit eug	28.41	14.10	5	0.26	8.71
Kahikatea (Dac dac)	0.37	0.19	1	0.0007	0.0227
Manatu (Pla reg)	5.97	2.99	23	0.25	8.42
Matai (Pru tax	0.32	0.16	1	0.0006	0.0193
Ti kōuka (Cor aus)	8.90	4.45	17	0.28	9.28
Totals (Sum):	**58.69**	**29.35**	**74**	**0.997**	**33.35**

Table 16: Average Above Ground/Below Ground biomass (kg) stored per stem, and total CO_2 sequestered by species for all 2011 Plots and per Hectare.

2012 Plantings

Stocking and Composition

Plot 12-1 is located on a north-north-east facing (30°) steep (30% slope) mid-slope with a sandy-clay soil type. It appears through numerous adjacent slips to be slip prone and rapid-draining. The area was planted at a low density with ngaio, akeake (*Dodonaea viscosa*) and a small component of akiraho (*Olearia paniculata*) and tī kōuka.

The plot itself, a 100m^2 (10 x 10m) area, comprised only ngaio and akeake in 2012 at time of planting but appears to have been infill planted with tī kōuka and additional ngaio and akeake to supplement existing plantings and possibly some mortality, shortly afterwards (inferred given comparable size).

Initial stocking was low, with the PSP having an initial stocked density of 700 SPH (400 SPH ngaio, 300 SPH akeake respectively). This low number of seedlings planted per hectare is likely to have been a conscious choice to improve survival in a site with high moisture stress/deficit and grass competition (Norton 2012).

Plot 12-2 represents a site that is on lower mid-slope down to toe-slope, with an easterly aspect (East-North-East) planted predominantly in ngaio and akeake, and tī kōuka, and with a smaller mahoe (*Melicytus ramiflorus*) component. The planted area is sheltered (from both wind and excess sunlight) at the lower reach of the incised gulley, and has notably more moist soil likely given the lower slop and slope position

This plot was originally planted at 2400SPH probably reflecting the better site conditions (eg: higher water availability and shelter) in comparison to the area represented by Plot 12-1.

Plot 12-1

Sampling as at 2021 showed (Table 17) a higher level of stocking (100% increase) of the Akeake component to 600 SPH, and addition of a tī kōuka component of 500 SPH as a result of infill planting. Ngaio stocking remained the same at 400 SPH, however given re-sampling in 2013 and 2015 showing mortality of 2 planted ngaio seedlings, and 2 of the ngaio measured in 2021 being of small size, it can be inferred that the lost ngaio were replaced via infill planting also. Total stocking of all as at 2021 is 1500 SPH, more than double the original planting, but still quite low for a planting of this age. Considering the infill planting that has occurred, and the overall increase in stocking from the initial planting, outlining the change in species composition is a merely a snapshot of the site at planting and at present rather than a visual representation of mortality.

Species	Stocking 2012 – Stems per hectare	Stocking 2021- Stems per hectare	Percentage Change (%)
Ngaio (Myo lae)	400	400	*nc*
Akeake (Dod vis)	300	600	+100%
Tī kōuka (Cor aus)	0	500	-

Table 17: Species composition and stocking change from planting (2012) to present (2021).

Initial composition seen below an almost even split of ngaio and akeake (Figure 33). A small number of akiraho were observed just outside of the plot boundaries, and in the surrounding area, but it was not present within the plot initially or at remeasurement.

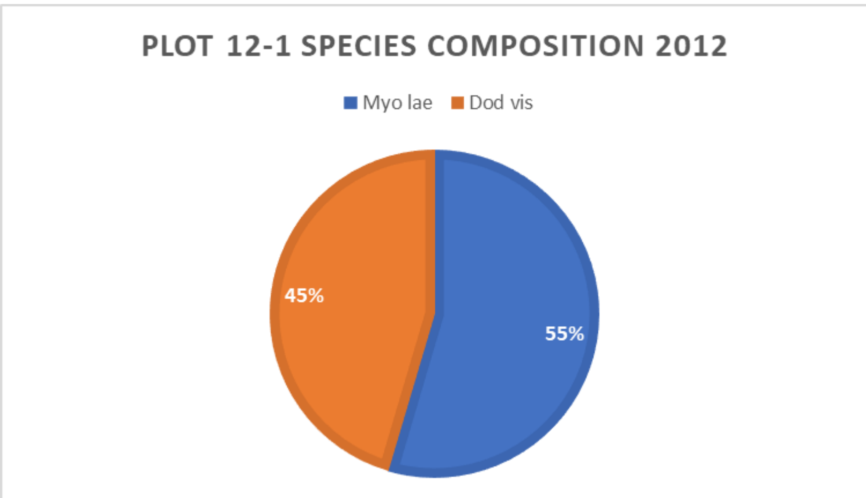

Fig 33: Plot 12-1 Species composition at time of planting (2012) Percentage of total stocking (700 SPH)

The current species composition includes a large ti kōuka component (Figure 34). This may be a questionable choice long-term, given the dry, exposed, free-draining nature of the site.

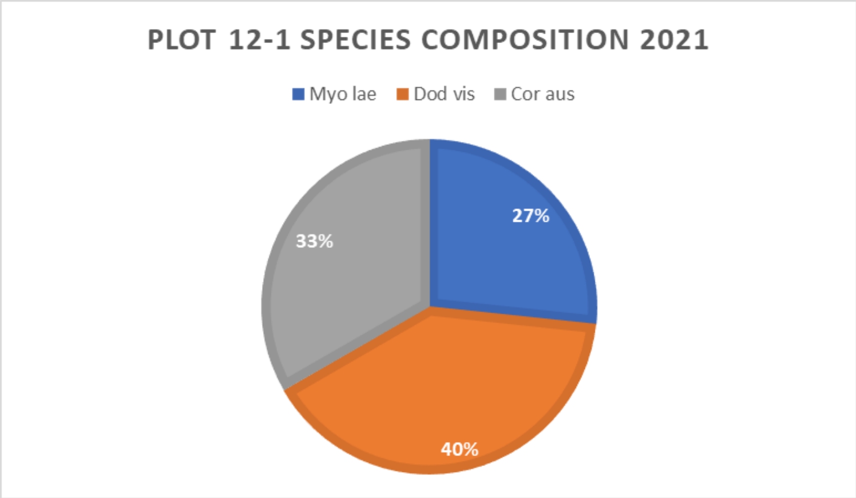

Fig 34: Plot 12-1 Species composition at time of sampling (Autumn 2021). Percentage of total stocking (1500 SPH)

The drone photography (Figure 35) shows a low-moderate degree of crown closure, with 66/121 grid intersections contacting vegetation, indicating 54.5% crown closure. Optically it appears lower than that given the light colouration of the ngaio and ti kōuka in the photo. Average crown diameters (CD) are estimated to be 2m for akeake, and 1m for ti kōuka. Ngaio has an estimated CD as 1.5m for the type 4 equation for carbon, for those saplings too small to assess via the type 3 equation which doesn't require a CD.

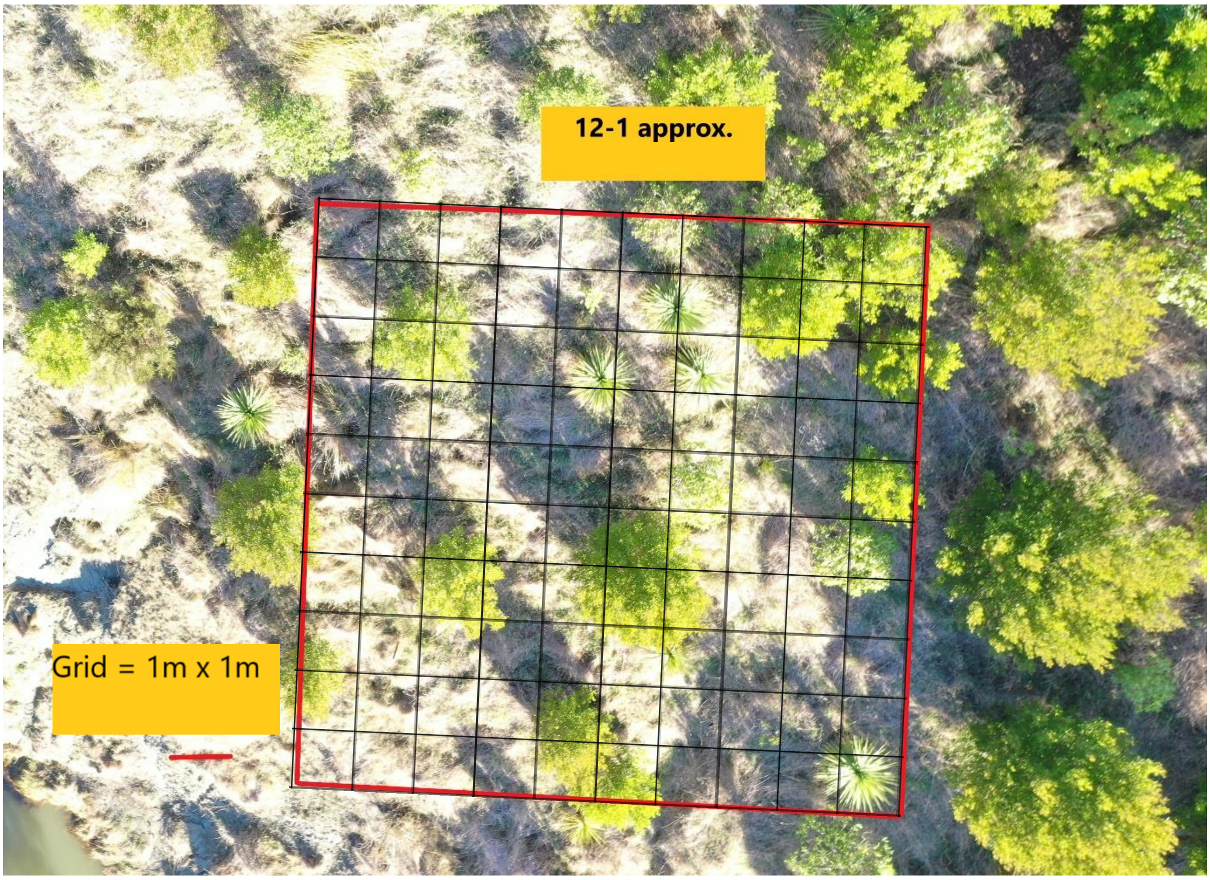

Figure 35: Drone photo of approximate location of Plot 12-1 (100m^2). 1m^2 grid spacing approximately.

Plot 12-2

Stocking at time of measurement currently sits at 2300SPH (Table 18), with species composition from planting in 2012 to present remaining almost contiguous, as does overall stocking (Figures 36 & 37). This appears, based on growth rates and crown closure, to be an optimal stocking level for this site at this age, although self-thinning to a lower stocking will almost certainly occur in subsequent years. No evidence of any infill planting was observed onsite, further indicating stability of the stocking and species choices.

Species	Stocking 2012 – Stems per hectare	Stocking 2021- Stems per hectare	Percentage Change (%)
Ngaio (Myo lae)	1100	1100	*nc*
Akeake (Dod vis)	500	500	*nc*
Tī kōuka (Cor aus)	600	600	*nc*
Mahoe (Mel ram)	200	100	-50%

Table 18: Species composition and stocking change from planting (2012) to present (2021).

The original composition as seen below (Figure 36), versus the composition at time of measurement (Figure 37) shows the partials mortality of the mahoe component and it’s minor flow on effect on relative species percentage composition of the other species with full survival.

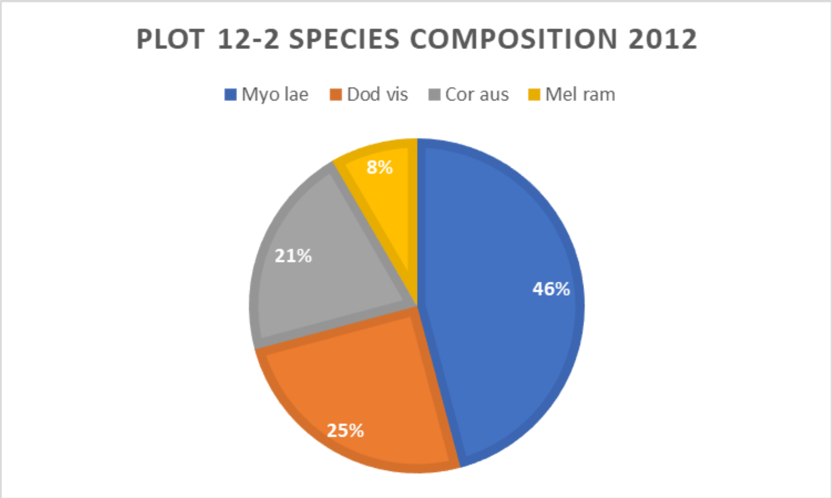

Fig 36: Plot 12-2 Species composition at time of planting (2012) Percentage of total stocking (2400 SPH)

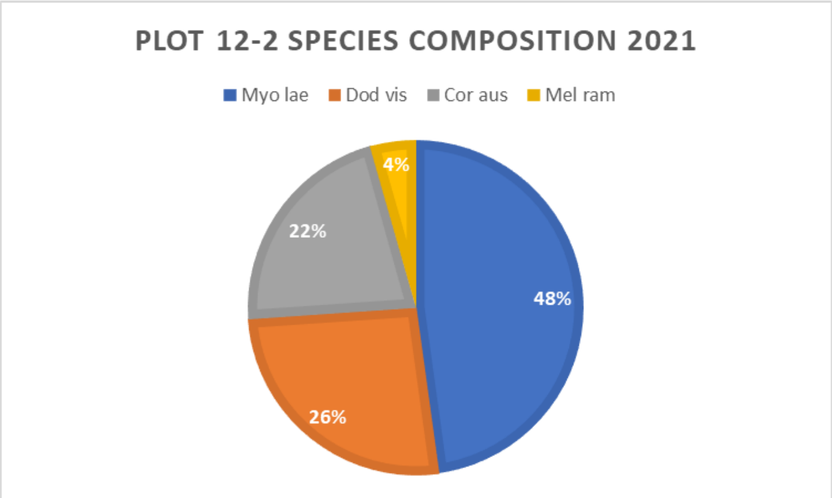

Fig 37: Plot 12-2 Species composition at time of sampling (Autumn 2021). Percentage of total stocking (2300 SPH)

The crowns of the ngaio and akaeake were very well developed for this site compared to the other 2012 planting (12-1), indicating favourable abiotic conditions for the target species on the site (Figure 38). 88/121 grid intersections contact vegetation, giving an estimated crown closure of 72.7%. Crown diameters are estimated to be 3m for both ngaio and akeake (noting the akeake have interconnected canopies and are difficult to discern), and 1.5m for ti kōuka.

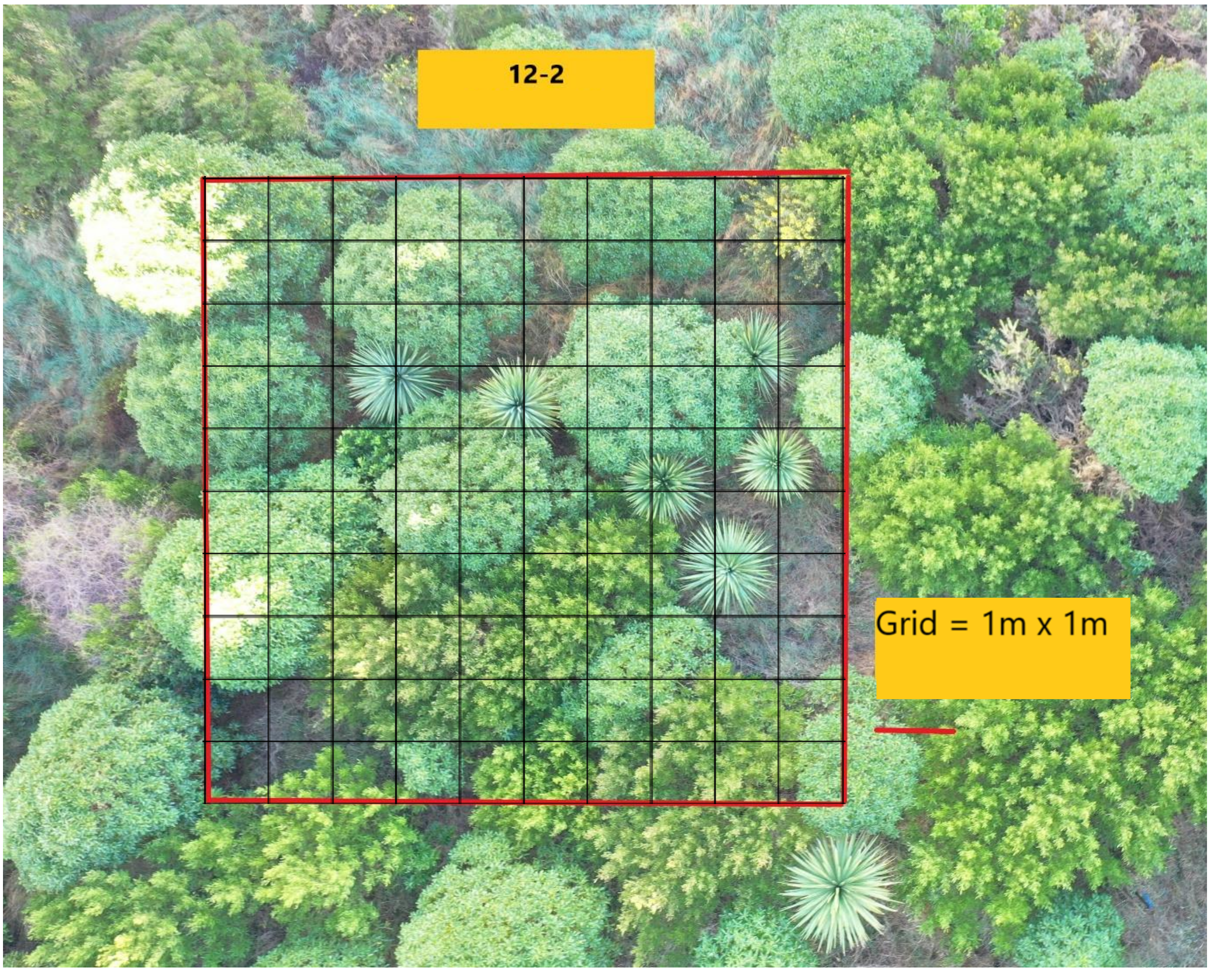

Figure 38: Drone photo of approximate location of Plot 12-2 (100m^2). 1m^2 grid spacing approximately.

Growth and Carbon Sequestration

Summary Statistics - Growth

Plot 12-1

The steep mid-slope plantings (plot 12-1) had considerably lower growth rates (Table 19) for all species occurring both there and on the North-East toe-slope site. This is likely due to abiotic factors (moisture stress, less shelter etc).

2012 Plantings (9-year period) Periodic Annual Increments (PAI): Plot 12-1			
Species	**PAI Height (cm/ann.)**	**PAI GLD (cm/ann.)**	**PAI DBH (cm/ann.)**
Ngaio (Myo lae)	22.08	0.58	0.53
Akeake (Dod vis)	38.89	0.92	0.34
Tī kōuka (Cor aus)	15.76	0.54	0.56

Table 19: 9-year periodic annual increment (cm) vs species for plot 12-1

Plot 12-2

The periodic growth rate of the denser lower toe-slope site (Table 20) can't be attributed to species given the comparable species mix and is likely due to the surround shelter and high soil moisture of the site.

2012 Plantings (9-year period) Periodic Annual Increments (PAI): Plot 12-2			
Species	**PAI Height (cm/ann.)**	**PAI GLD (cm/ann.)**	**PAI DBH (cm/ann.)**

Ngaio (Myo lae)	32.80	0.81	0.57
Akeake (Dod vis)	47.78	1.46	0.42
Tī kōuka (Cor aus)	36.89	1.17	0.96
Mahoe (Mel ram)	34.44	0.58	0.18

Table 20: 9-year periodic annual increment (cm) vs species for plot 12-2

The aggregated height growth for all of the 2012 plantings shows consistent growth rates for both sites in the initial 3 years following planting (Figure 39), but then divergence at time of remeasurement in 2021. Interestingly the divergence in relative height growth does not appear statistically significant except for ti kouka, as the height ranges for ngaio and akeake overlap for both sites, albeit barely, and at the data tails (ie: <2.5% of the range). The height growth divergence will likely be statistically significant for both ngaio and akeake at a future date given the differing abiotic constraints or the sites.

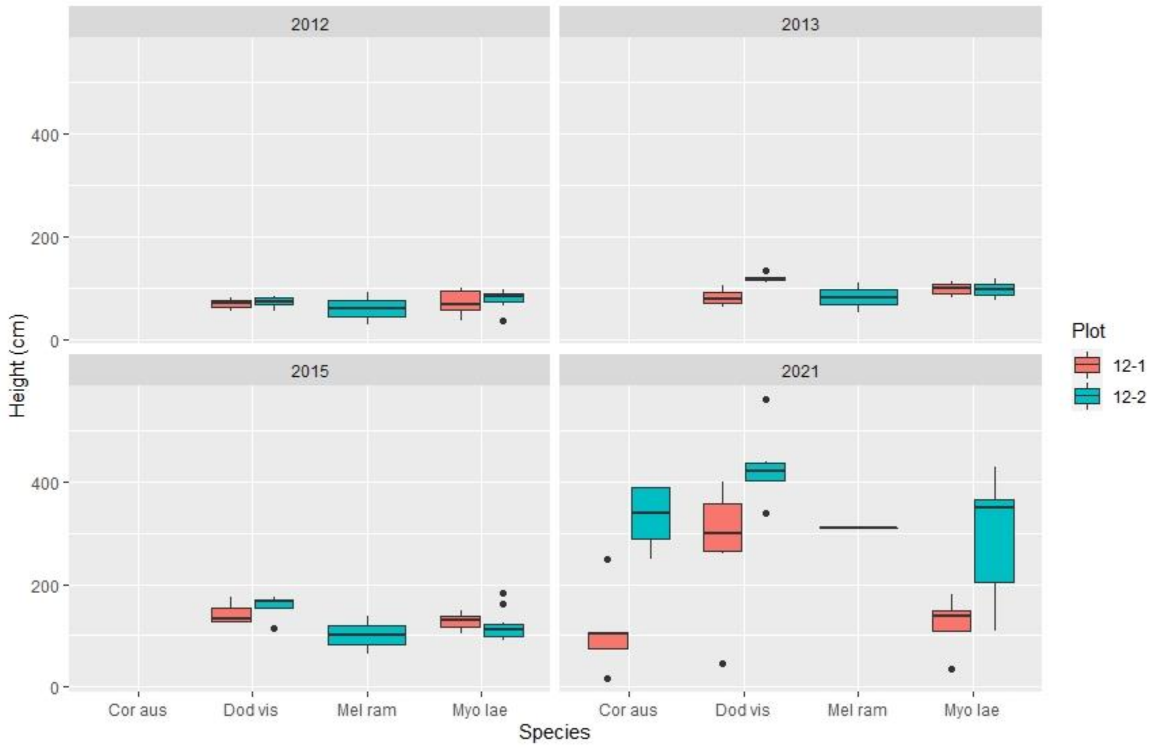

Figure 39: Height vs Species by Plot/Measurement year boxplots for all 2012 Plantings.

Given the height growth range overlap, it is still viable to aggregate the height growth data vs species/measurement year to predict growth moving forward (Figure 40). The LOESS regression lines of the scatterplots show gradually plateauing height growth for ngaio and mahoe (nb: only 1 mahoe was present), but a continuing upwards trend for akeake.

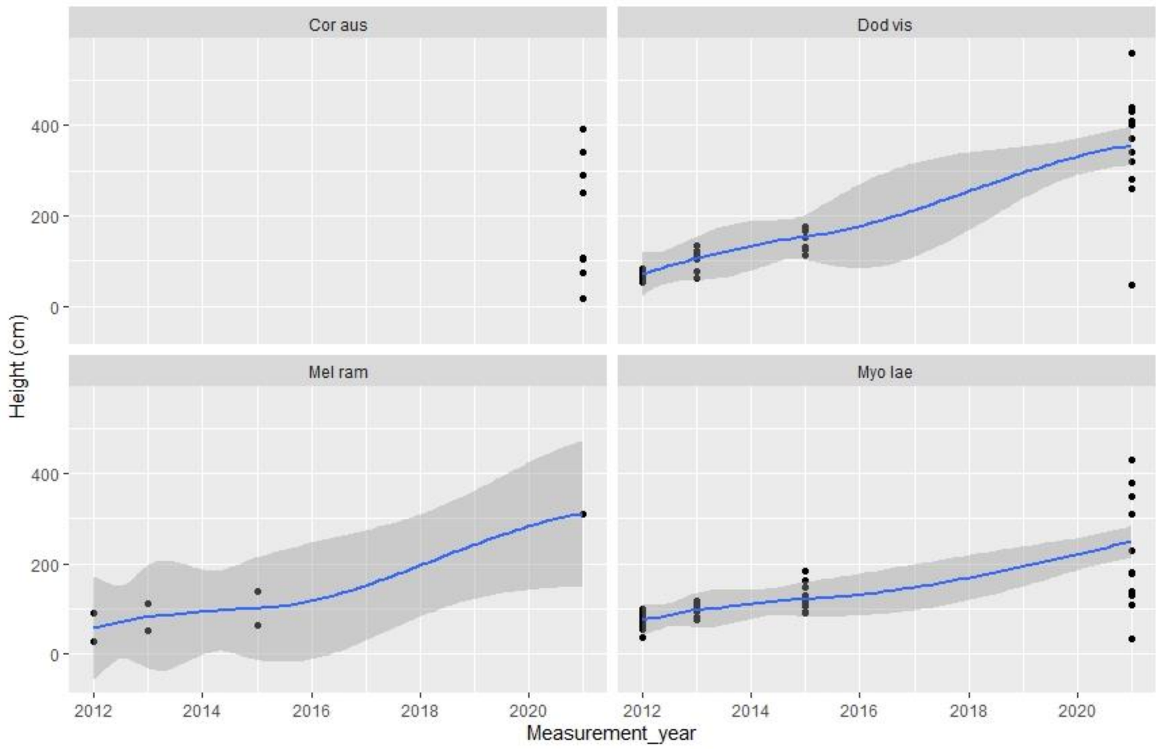

Figure 40: Height growth vs Species/Measurement year scatterplots for combined 2012 Plantings. With LOESS lines and CL bands.

GLD and DBH boxplots for the 2012 plantings show range overlap for ngaio for GLD between both sites (Figure 41) but not for akeake or ti kōuka. The DBH boxplot (Figure 42) shows overlapping range for all species for both sites, but this is reflective of the few akeake and ngaio at the site 12-1 represented having a measurable DBH unless being an original (non-infill) planted specimen and being one of the faster growing specimens on the site.

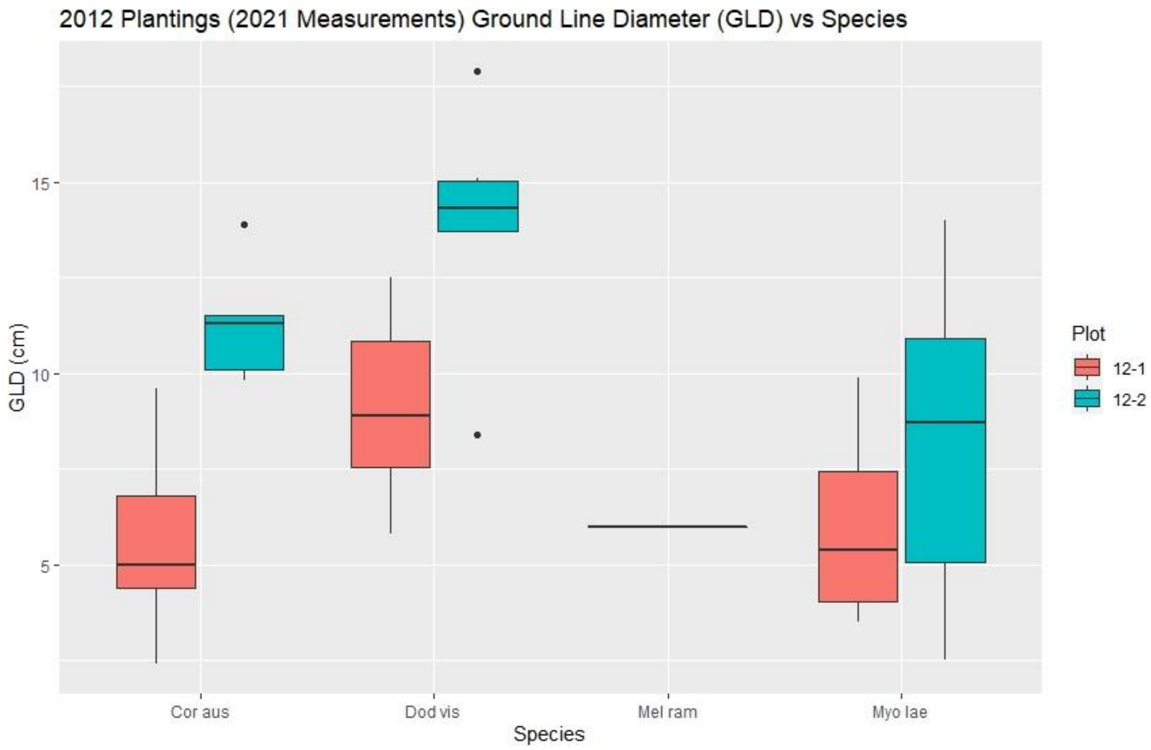

Figure 41: GLD vs Species/Plot as at 2021 for 2012 plantings.

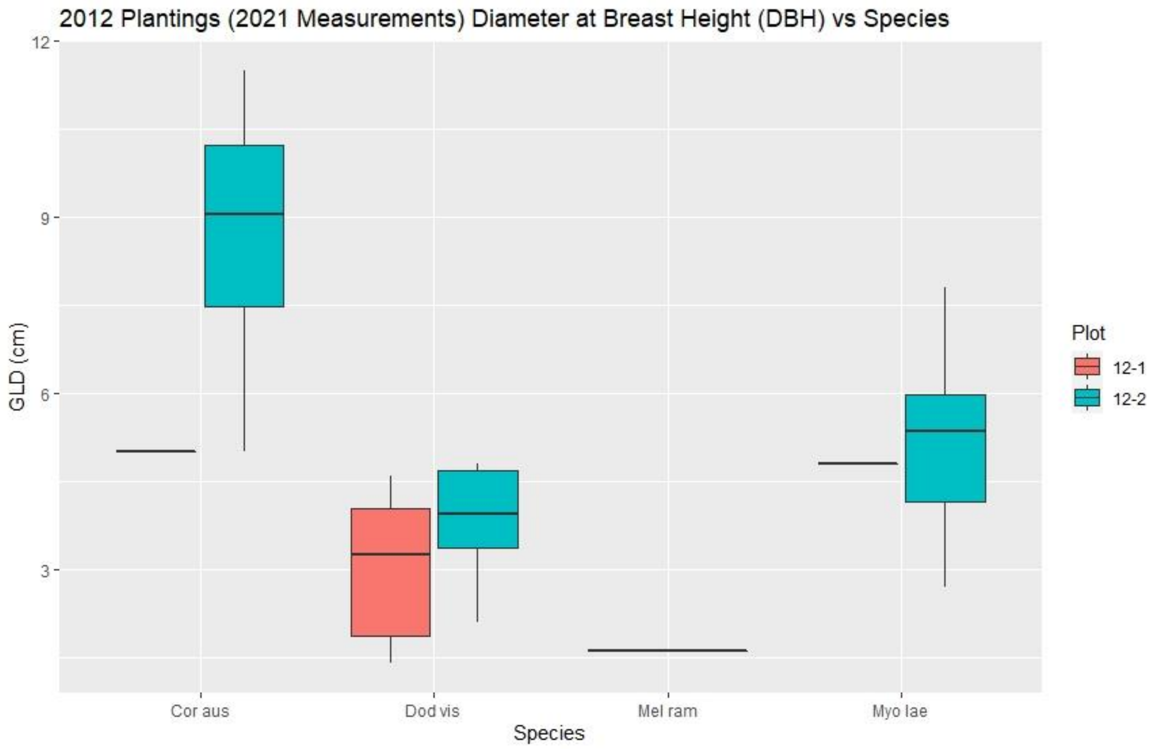

Figure 42: DBH vs Species/Plot as at 2021 for 2012 plantings.

Summary statistics – Carbon

The estimate of sequestered CO_2 is higher than for the 2011 plantings (Table 21), mostly due to the high growth, low mortality and dense canopy observed in the North-east facing toe-slope (plot 12-2), but also due to the broad canopy development found in both akeake and ngaio. The figure is also slightly underestimated given the average AGB/BGB includes the smaller specimens of ngaio/akeake found on the mid-slope site (12-1) which had narrower canopy and generally lesser GLD and DBH.

Combined Carbon Estimates – All 2012 Plantings					
Species	**Average AGB + BGB per Stem (kg est.)**	**Average Carbon per Stem (kg est.)**	**# Stems**	**CO_2 stored (tonnes/Combined Plot area)**	**CO_2 stored per hectare (tonnes per hectare est.)**
Ngaio (Myo lae)	19.63	9.81	15	0.54	26.99
Akeake (Dod vis)	26.31	13.16	12	0.58	28.94
Tī kōuka (Cor aus)	4.51	2.25	10	0.08	4.13
Mahoe (Mel ram)	0.26	0.13	1	0.0005	0.0238
Total (sum)	**50.71**	**25.35**	**37**	**1.2005**	**60.0838**

Table 21: Average Above Ground/Below Ground biomass (kg) stored per stem, and total CO_2 sequestered by species for all 2012 Plots and per Hectare.

Kahikatea – Kate Pond Edge

Growth

The small cluster of 10 tagged kahikatea have all survived since initial planting in 2006 and appear to have vigorous growth despite observed historic animal damage (browse and mechanical) on all stems (Table 22).

2006 Plantings (15-year period) Periodic Annual Increments (PAI): Kahikatea (Kate Pond)			
Species	**PAI Height (cm/ann.)**	**PAI GLD (cm/ann.)**	**PAI DBH (cm/ann.)**
Kahikatea (Dac dac)	25.7	0.711333	0.532

Table 22: 15-year periodic annual increment (cm) for the 2006 Kahikatea plantings

Height growth has been slightly variable between the stems (Figure 43) but with the sample size so small (n =10) nothing can be inferred about this difference.

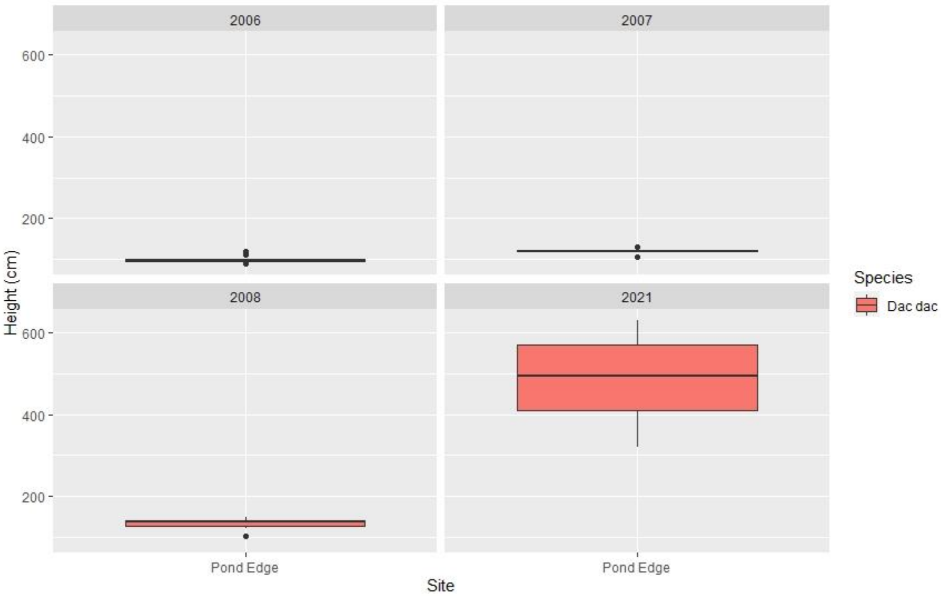

Figure 43: Ht vs Measurement year/Site as at 2021 for the 2006 kahikatea plantings.

The LOESS regression of the scatterplot (Figure 44) shows the variation clearly through wide confidence limit bands, and also through an inflection point indicating growth is slowing, but this may not be the case for kahikatea given its natural maximum height.

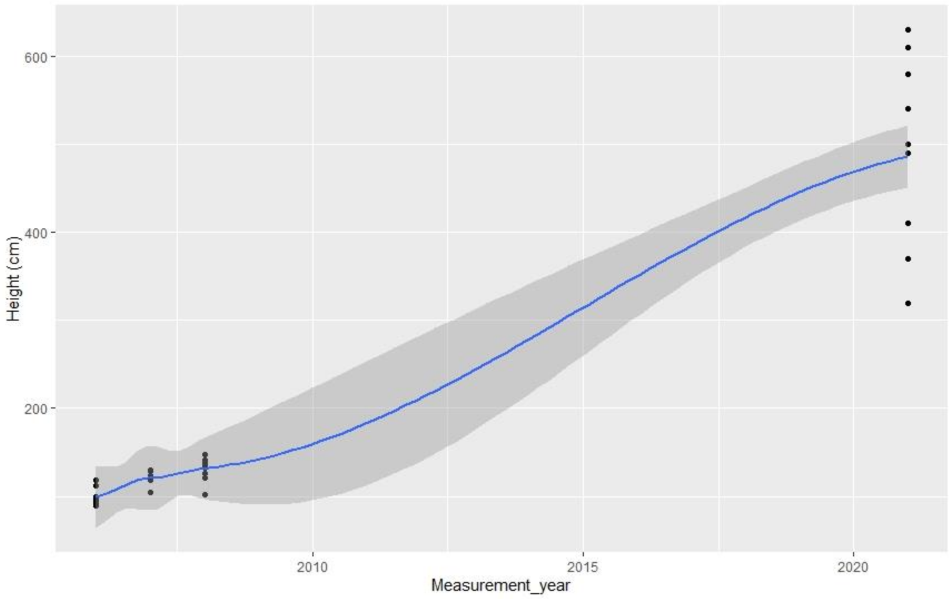

Figure 44: Height vs Measurement year scatterplot with LOESS regression for the 2006 kahikatea planting at kate pond.

GLD and DBH ranges are relatively narrow, indicating consistent growth for all stems at the site (Figures 45 & 46)

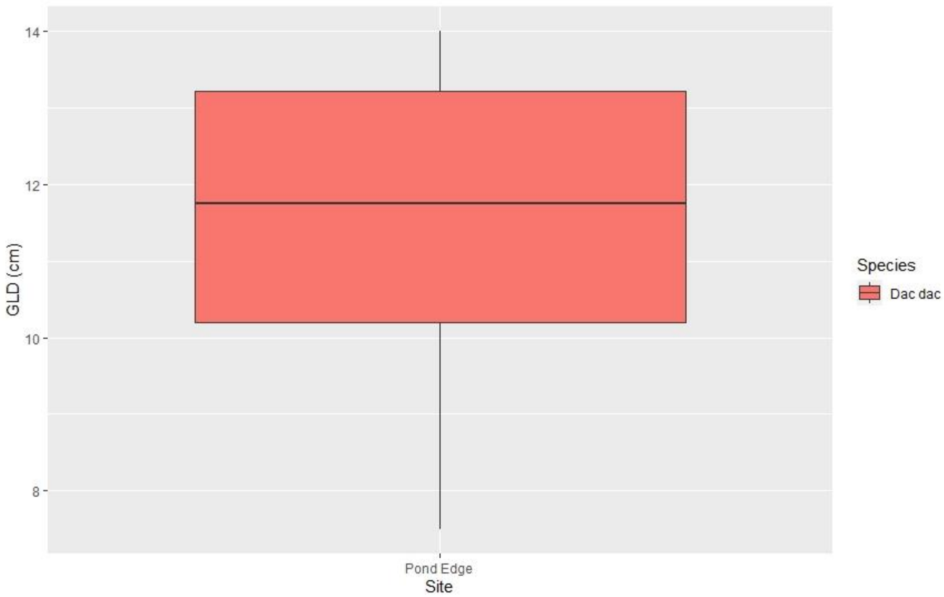

Figure 45: GLD as at 2021 for the 2006 kahikatea plantings.

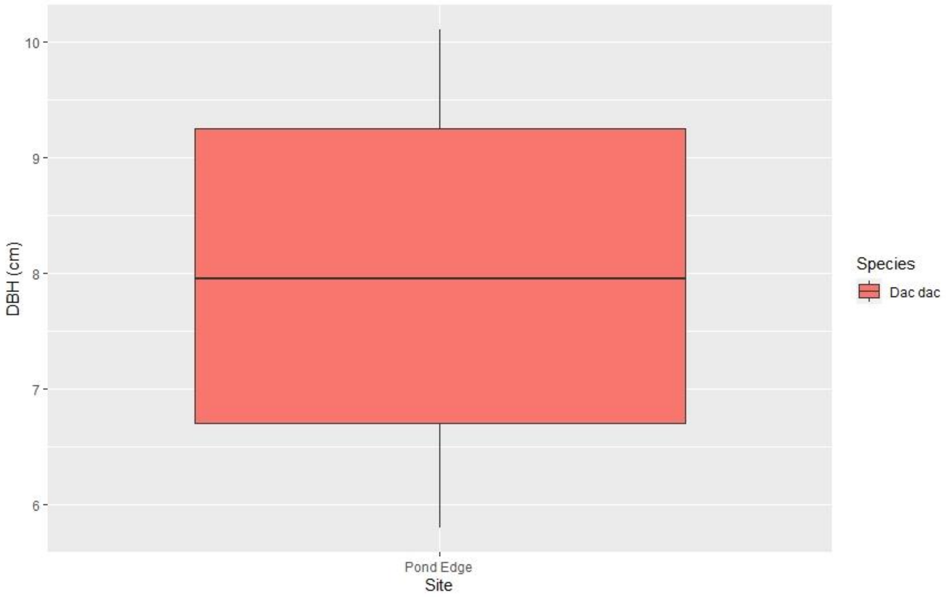

Figure 46: DBH as at 2021 for the 2006 kahikatea plantings.

Black beech

Growth

Three beech sites were measured in 2021: a north facing site, a south facing site, and a ridgeline site. The largest number of Black beech (*Nothofagus solandri*) were planted on a low-elevation ridge site in 2009. This planting had on-site irrigation at the early stages to prevent desiccation on the exposed fast-draining site, and the beech was interplanted with tree lucerne (*Cytisus proliferus*) as a nitrogen-fixing nurse crop, and kanuka (*Kunzea robusta*). Given approximately 11 growing seasons since planting and a seedling age of <= 1 years at planting (Cavanaugh 2021), it can be assumed the actual age of the stand is 13 years. 92 live trees were measured, with a further 5 dead stems noted. Spacing was around 2-2.5m on average, (interspersed with tree lucerne and kanuka) and form of the beech was generally straight (few multi-stem trees) with vigorous growth relative to age. Animal damage was minimal at this site, but ample pig-sign was observed.

The South-facing site was planted in 2010, giving the trees an approximate age of 12 years (as per above logic). The site was very open, with 21 beech measured, and grass approximately 0.6m heigh surrounding the planted beech along with a small number of kanuka adjacent to the trial on the eastern edge. The trees were widely spaced (>3m on average) and form was generally conical. All trees appeared vigorous. Some historic browse damage was observed on a low number of trees.

The North-facing site was in fact 3 distinct sub-sites with small numbers of beech planted in each for a total of 16 measured beech, these were also planted in 2010, being approximately 12 years old at time of measurement. The beech were interplanted with a variety of other species, primarily kanuka, tarata, and kohuhu, along with smaller numbers of kowhai, manatu and totara. Matai may have been present in the original surrounding planting but was not observed. The North-facing beech had a moderate proportion of historic animal damage (deer browse) but were growing vigorously and had straight form given the high stocking with the surrounding species.

Height at time of planting, for estimating periodic growth of beech at all three of the sites, was estimated as 0.82m[7], and original GLD was estimated at 0.8cm (Cavanaugh 2021).

The periodic growth rates (11 year for the North/South facing sites, 12 years for the ridge site) showed clear variation between the sites, with the north facing site having significantly greater average height increment growth (Table 23).

2009/2010 Beech Plantings Periodic Annual Increments (PAI): North, South and Ridge sites			
Species	**PAI Height (cm/ann.)**	**PAI GLD (cm/ann.)**	**PAI DBH (cm/ann.)**
North-facing	63.17	1.26	0.99
South-facing	51.86	1.23	0.96
Ridgeline	43.24	0.94	0.74

Table 23: 11 and 12-year periodic annual increment (cm) for the three beech plantings

This was not reflected as a statistically significant difference when height ranges were compared (Figure 47), as ranges overlapped for the three sites.

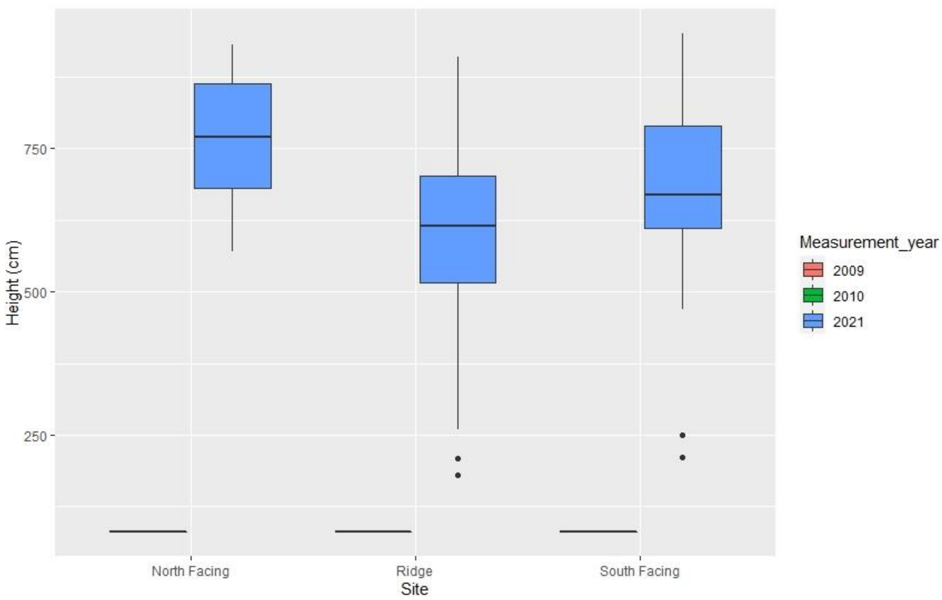

Figure 47: Ht vs Measurement year/Site as at 2021 for the 2009/2010 beech plantings.

[7] This being the average planted height of the unlocated tagged beech trial

This did allow aggregation of the height growth data though, with the LOESS regression of the scatterplot (Figure 48) appearing to show a plateau of height growth, however this height is well under natural maximums for black beech (Wardle 1984), and likely represents a local inflection point of slowed growth prior to growth of dominant stems and suppression/mortality of other stems. A rough growth model in an earlier study using the growth data from the planted beech in conjunction with the height data from the remnant beech patches in the reserve, estimated that height growth may plateau on average around 10.5m, but that a maximum height of around 20m was possible (Kernahan & Morice 2021). .

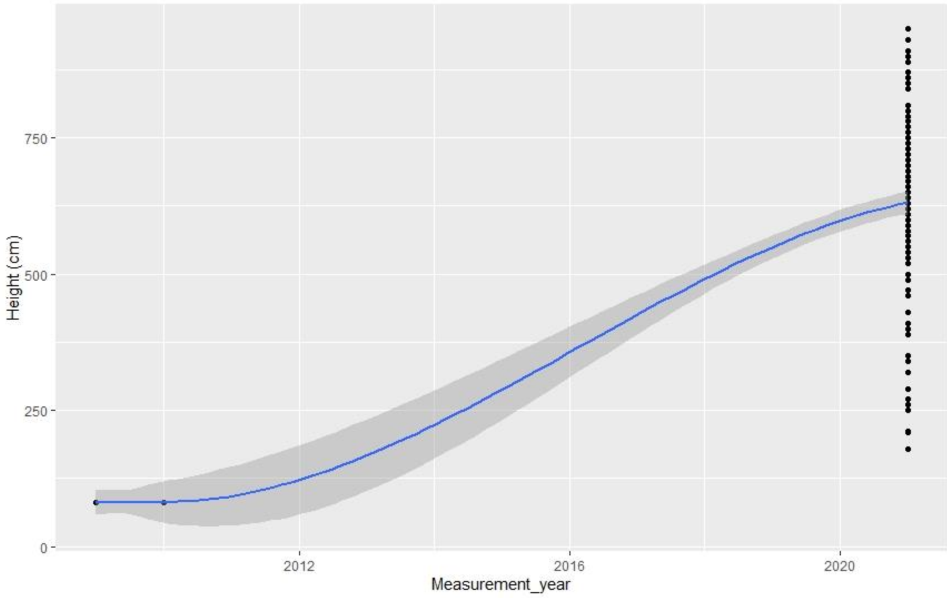

Figure 48: Height vs measurement year scatterplot with LOESS regression lines and CL bands for all beech plantings

Similarly to the height ranges, the GLD and DBH ranges all overlapped (Figures 49 & 50), indicating no significant difference between the sites, as was found in an earlier study which conducted an ANOVA between the three sites for the same metrics (Kernahan & Morice 2021).

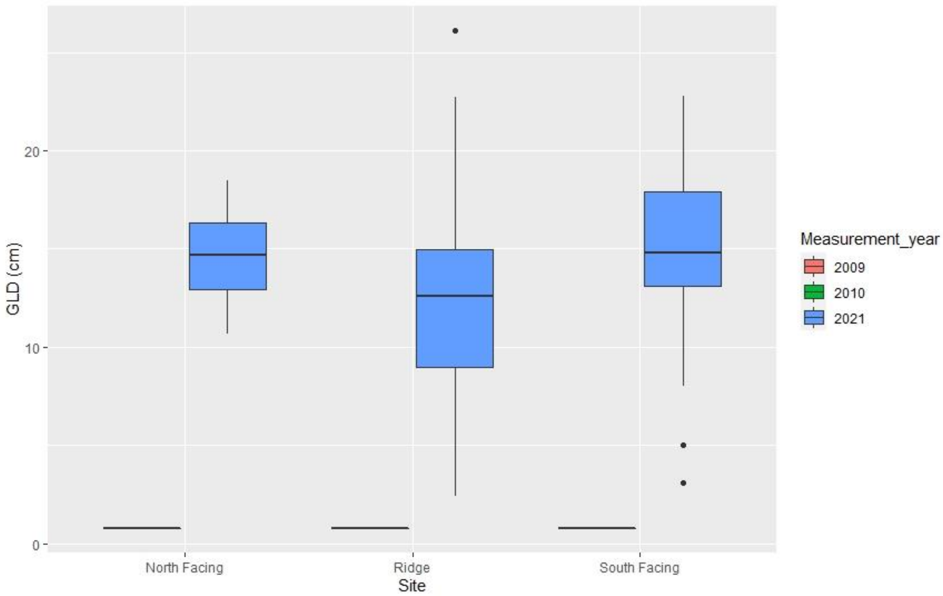

Figure 49: GLD vs site boxplots for the 2009/2010 beech plantings.

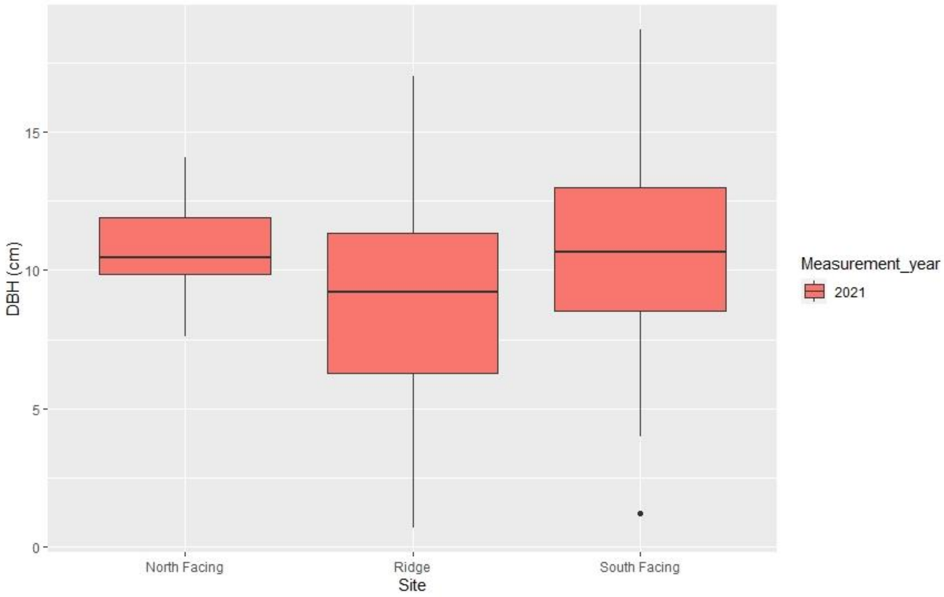

Figure 50: DBH vs site boxplots for the 2009/2010 beech plantings.

Aggregated Data Comparison

Growth

As noted previously, The GLD and DBH PAIs are indicative (the DBH especially), given the need to use upper-limit nursery averages for initial GLD to be conservative in estimation, and the fact that many trees were multi-stem with only the dominant stem DBH used for modelling purposes. In light of the latter, which renders DBH PAI estimates unusable for comparing aggregate growth across sites and plantings, the height and GLD growth increment data provide the most accurate indication of site-by-site difference. Although, it should be noted that height and GLD growth are enhanced by higher and lower stocking rates respectively, which vary by site.

The aggregated PAIs for height (Figure 51) show quite pronounced variation in periodic height growth by site, for species occurring on multiple sites. This is most pronounced for totara and ti kōuka, with both having multiple times higher (or lower) annualised height growth between differing sites. It's important to take this in context however: the lower ti kōuka growth rates at plot 6-2 may reflect plateauing of growth (as seen in the regressions) as they approach a local maximum height some 15 years in, and growth generally being faster at earlier development stages (eg: sigmoidal or logarithmic growth). For the totara, the impact of infill planting may distort the growth rates actually observed, as the infill planting year is not known, so the PAI period used may be too large. These factors notwithstanding, it can be observed that the sites represented by Plots: 8-1, 8-4, 8-5, 11-4 and 12-2; generally had superior growth to the other sites over the same-length growing period. For the individual plantings, only the beech can be assessed against other sites, but in that case the North-facing site interplanted with other species had the greatest proportional height growth rate.

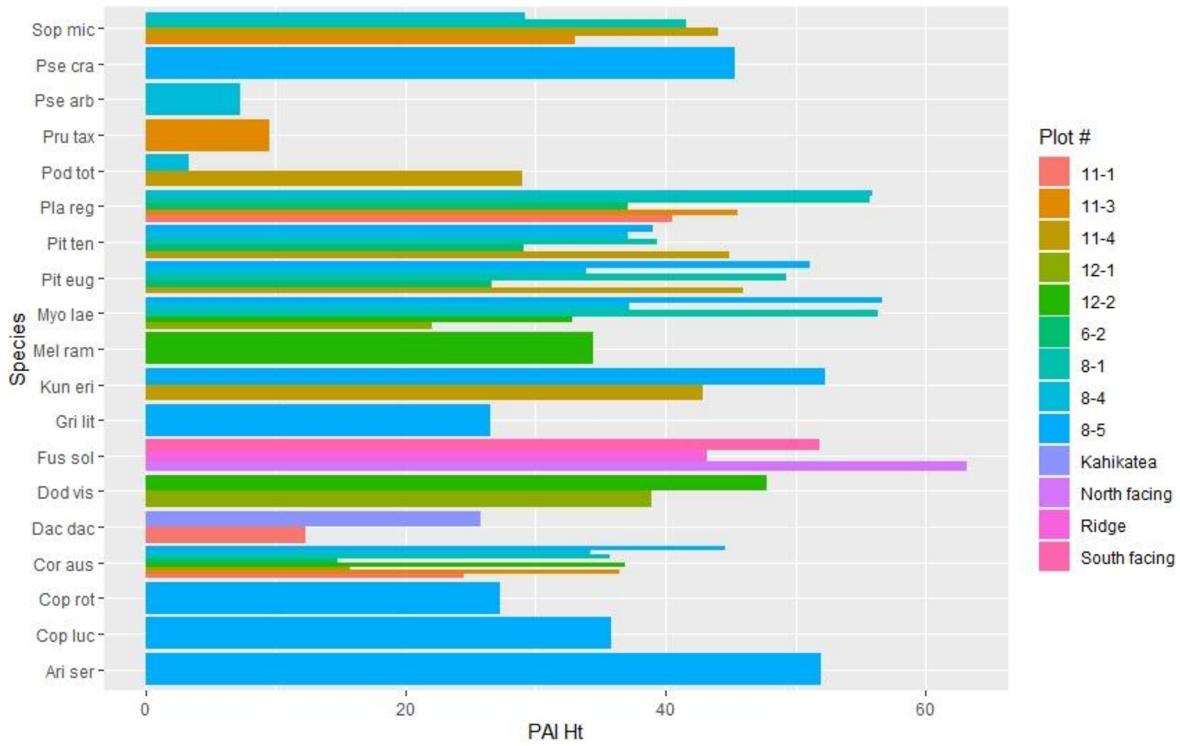

Figure 51: PAI Height growth (cm) of species on all sites

The aggregate GLD PAI data (Figure 52) gives a more nuanced result, as while there is clear variation between sites, it varies by species as to which site resulted in greater GLD growth. Kanuka, kohuhu, tarata and kowhai for example, performed slightly better on site 11-4 versus the 2008 planting areas (8-1, 8-4, and 8-5) which had the best height growth for a range of species present. Similarly, ti kōuka saw strong GLD growth on sites 11-1 and 11-3, which were marginal growing sites for the other planted species still present there (manatu, kowhai) compared to other sites. There was also strong variation between the growth of akeake and ngaio between the two 2012 plantings, although as stated previously, this is likely the impact of soil-moisture/shelter differentials between the sites, and later undocumented infill planting confounding the PAI calculations. The individual plantings again favour the North-facing, intermixed site for the beech with regards to growth, as per the height PAI results.

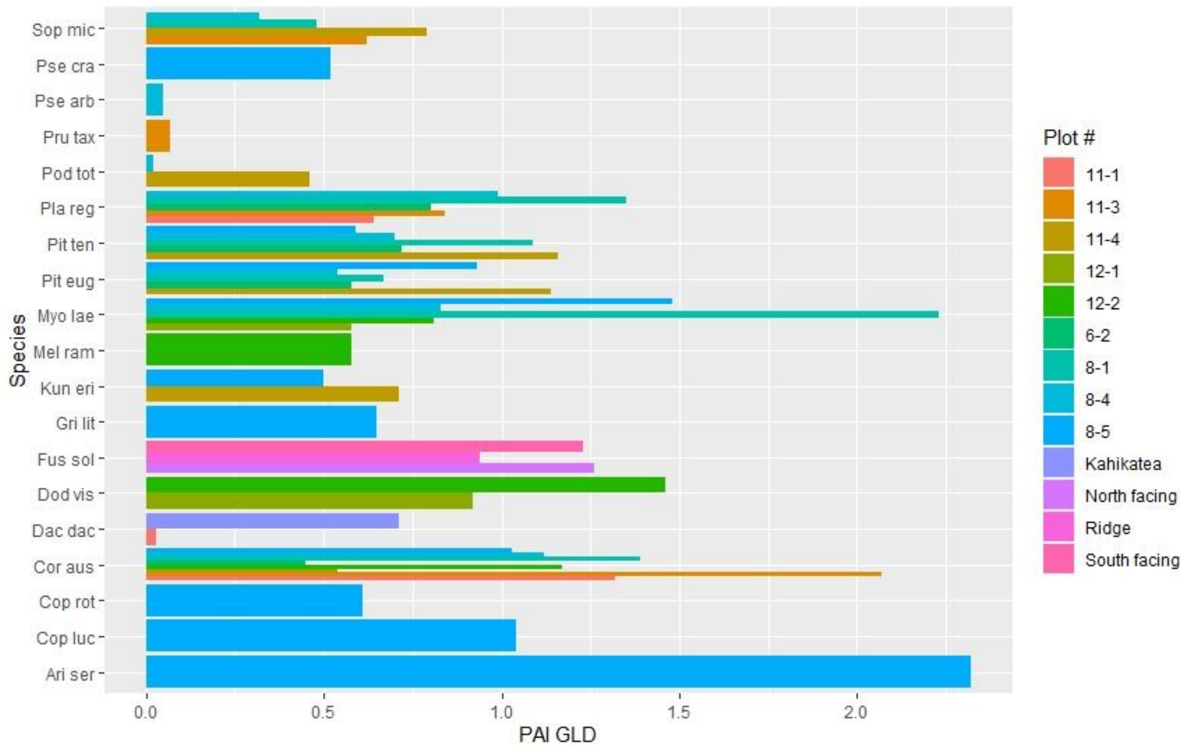

Figure 52: PAI GLD growth (cm) of species on all sites

Carbon

The carbon sequestration data for the bounded plantings was recalculated to assess the per-stem carbon sequestered range (in kg) versus plot by species (Figure 53). A small number of very strong outlier data points (> 3rd Quartile + 3 x Inter-Quartile range) were removed to ensure the comparison was more accurate. These strong outliers were mostly ngaio, where a large GLD led in some cases to an overestimation of AGB and therefore carbon stored. The combined data boxplots show that per-stem carbon ranges generally overlap for all plots except for ribbonwood, where the poor growth sites 11-1 and 11-3 have lower sequestration, and the two 2012 plantings (12-1 and 12-2) where the poorer growing site with infill planting (12-1) can't be accurately assessed as a comparator.

The range overlap suggests that there is no statistically significant difference (within wide ranges) between sites for carbon sequestration per stem to-date, even where there is variation between height and GLD growth.

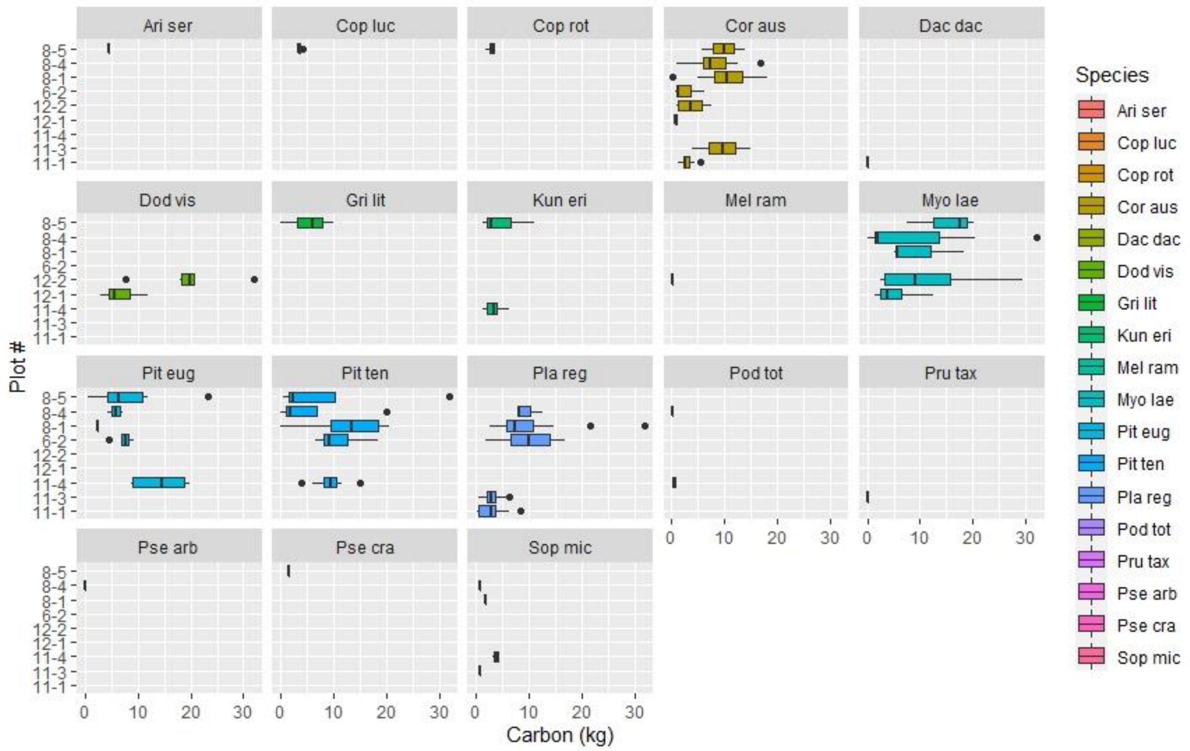

Figure 53: Per stem Carbon sequestration (kg) of species on all bounded sites

Discussion

Given the high degree of variation between the various plantings with regards to composition and stocking, as well as the various sites themselves, it's necessary to assess them individually to accurately gauge how they've performed. However, they can be grouped by planting year for the purposes of displaying the difference in growth between sites and their associated planting mixes over time.

2006 Plantings (Plot 6-2 and Kahikatea)

The mixed planting site (6-2) looked to have a degree of moisture stress present even though the slope profile went from lower mid-slope to toe-slope, possibly due to the degree of slope and the North-facing position. This stress was noted in the condition of the foliage (generally small crowns present) and lower crown closure than would be expected for the site at its age. Out of the two pittosporum species, kohuhu generally had better survival on this site than tarata. and as palatability can be ruled out as a reason (Norbury 1996), it may be that it had better moisture stress tolerance given the slope and aspect of the site.

By comparison the individual kahikatea plantings seemed to have no limiting factors affecting their growth other than the historic animal damage observed. Kahikatea fared significantly more poorly where planted at other locations within the reserve, often subject to trampling or uprooting from feral pigs prior to recent control efforts. The success of this planting is likely due to the direct proximity to Kate pond (pond edge) providing sufficient soil moisture and a barrier on one side and being comparable to natural conditions where kahikatea would thrive (Waring 2017). The surrounding dense, naturally regenerating bush, also limits access to the trees for herbivorous pests and pigs to a degree which has lily contributed to the success of the plantings.

2008 Plantings (8-1, 8-4 and 8-5)

The Pond edge planting (8-1 and surrounds) is a very different site to the other 2008 plantings, given its position on the south bank of Kate pond and North facing aspect, both of which have a strong influence on growth. The planting had both a high degree of crown closure and significant growth (height and GLD in particular) of all surviving planted species, and also a high survival, with loss of only kaikomako, and retaining a high stocking rate (3700 SPH). The ngaio in particular were well adapted to the site and exhibited high growth. Similar to the 2006 kahikatea planting, It is likely that proximity to the pond (higher soil moisture and a natural barrier to browsing species) may have played a role in initial success. The presence of seedlings in the subcanopy would suggest that natural regeneration is beginning for the site and that it has long term stability beyond the life of the planted trees.

The other two 2008 plantings (8-4 and 8-5) were located on a South-Facing lower slope, with wind protection on the West, North, and Eastern sides from the surrounding small hills which may have reduced the risk of drought on this site, but conversely would have increased the risk of frost damage given reduced daily photo-period and frost pooling in the "valley" terrain effect of the site and given it's minimal slope. It's difficult to assess what degree of actual mortality there was between planting and present however, given the infill planting that has occurred for 8-4 in particular.

For 8-4 and surrounds the open canopy (low crown closure) relative to high stocking does suggest that site conditions have had a negative impact on growth even notwithstanding the number of ti kōuka (which have small crowns). Planting of a greater proportion of kohuhu and tarata versus the ngaio and ti kōuka used would likely have had a better result given their presence in the canopy in the surrounding area and growth of both on the site. Kohuhu and tarata are also both noted to be frost hardy (Bannister et al. 1995). It should also be noted that the site had high soil moisture, with sedges (*Cyperaceae sp.*) present, which also may have impacted planted species preferring greater soil drainage.

8-5 by comparison nearby, has a denser canopy with a much higher degree of closure due to the differing species mix. A number of seedlings were observed in the sub-canopy further indicating the health of the site and long-term trend towards replacement via natural regeneration. It should be noted that the transplanted trees and shrubs will have had higher vigour given more developed roots and possibly better adapted mycelium (Mullin & Howard 1973), but the generally high performance of all plantings on the site supports that the species mix was more appropriate for 8-5 than 8-4, and may have been more typical of the species mix occurring on a comparable natural site.

2009/2010 Beech Plantings

The beech growth rates were previously calculated to not be statistically significantly different (Kernahan & Morice 2021) between the 3 sites (North-facing, South-facing, and Ridgeline), but there were still observable differences in growth between the sites. The North-facing plantings (2010) were interplanted with a mixture of other indigenous species, mostly angiosperms, and there is some evidence to suggest this may be beneficial to growth (Tulod & Norton 2019), but it would also be confounded with the site being a steep upper slope, which given the aspect would allow for maximum light exposure, which would be a stronger contributor to growth.

The ridgeline site (2009) would have a similar (or better) photoperiod but being exposed to wind and free draining would have had moisture constraints, hence its reduced relative performance. It is unclear whether the nitrogen-fixing tree lucerne nurse crop and irrigation present at planting, was a key contributor to survival or growth of beech on the ridge site, as it can only be compared with the other sites in terms of growth, where it performed roughly on par with the South-facing site, indicating some abiotic constraints may still exist.

The open grown beech in the South-facing site are partially sheltered by surrounding hills on 3 sides, but also would have a reduced photoperiod as a result. Given the open planting (wide-spacing) and high grass present surrounding the planting (only a factor at time of planting), a wider range of Heights, GLDs and DBHs were observed at this site than the other two sites: as would be expected.

In comparing the three sites it would see that an optimal planting strategy for beech to maximise growth/survival would be to position plantings on mid to upper slopes and interplant them with a range of other species. Aspect cannot be controlled for that strategy but the north facing sites will likely have the highest growth rates.

2011 Plantings

The valley bottom in which 11-1 and 11-3 (and surrounding similar plantings) occur, had substantial cover of exotic grasses, with an average of 62cm grass height noted throughout the plot at time of sampling, (mid-late autumn). While the restoration plan calls for chemical spot preparation prior to planting into grassy areas (Norton 2005), there still would have been a high risk of frost damage (frost pooling due to low albedo and dew) and soil moisture competition (Ball et al. 2002), all of which may have contributed to the substantial mortality observed at both plots, even given subsequent infill planting. Likewise, while active pest control was ongoing at time of sampling, a resident feral pig population had caused substantial soil damage and uprooting of some planted seedlings at both sites.

The latter issue has since been addressed via a largescale cull of pest species (pigs the small number of deer in the fenced perimeter), but the abiotic (frost) and biotic (frost damage enhancement, moisture competition) caused by the grass species remains for any further infill planting undertaken. It may be beneficial to have future infill planting look to use different species at the 2 sites and at much higher density to provide shelter suppress grass growth, as well as reducing frost damage risk via an increased albedo (Ball et al. 2002). Once established, it was noted that manatu and ti kōuka had moderate growth at both sites, which support putting more effort into early establishment and enhancing survival. Both species also have moderately high frost tolerance (Harris et al. 2001, Darrow et al. 2001) which should be a consideration for other species used to infill.

The upper slope 2011 planting (11-4) by comparison had no such issue with mortality, lower observed animal damage (minimal historic damage), and higher growth rates on average. There would obviously not have been a frost risk for an upper slope site (air flow downwards would reduce this risk), and being North-facing would have enhanced growth, as was observed. The mortality of the small matai and manatu components is also likely to have been due to them being a poor choice for the site (a steep, dry site) rather than the site as a whole having notable constraints, given the growth of the other species. The surrounding area plantings exhibit the same growth and crown closure as the plot (11-4), and while natural regeneration was not observed within the plot, it was adjacent to it, which indicates the success and future stability of the plantings. Passive observation of adjacent naturally regenerating bush, which was predominantly kanuka suggests that there will be a successional shift to kanuka dominance over time, less the scattered beech plantings nearby which will overtop the kanuka.

2012 Plantings

The two 2012 planting sites are quite different and resultingly, have had different growth rates (though they do not appear to be statistically significant differences). The mid-slope site (12-1) is difficult to assess given the substantially infill planting that has occurred, but the surviving original plantings all appeared to be relatively vigorous considering the moisture constraints of the steep, North-facing site, and likely to persist. This plot is reflective of the surrounding similar planting in terms of composition and stocking level, with Akiraho, though not present in the plot itself, noted nearby and having similar survival/vigour at its own low stocking level. Grass competition did not seem to be an issue (average height ~30cm) likely due to how dry the site is.

Unknown mid/long-term risk factors to the planting are likely to be terrain stability issues (eg: large slips or partial subsidence and resultant root damage) and drought events affecting an already moisture-stressed site.

By comparison the lower/toe-slope gulley bottom site (12-2) has undergone very little mortality within the plot area, with only one mahoe absent, although with the other surviving mahoe notably suppressed through extensive, repeated browsing. Overall, the site shows vigorous growth of all other planted species and expansive canopy growth of the Ngaio and Akeake.

It is likely that sheltering from adverse weather (eg: strong winds), provided by the sites positions in a deeply incised, narrow valley has been a contributing factor to the success of the site, as has the low slope position (less moisture deficit through sub-surface flow) and aspect (sufficient sunlight for growth, but less chance of sunscald of sun induced heat-stress). A final mitigating abiotic factor is proximity to the sea – sufficiently close to allow the temperature of the site to be moderated by sea-breezes but sufficiently far to avoid negative abiotic effects from salt-spray carried by said breezes.

Conclusion

As stated in the introduction: the sites measured have a range of different species planted, different stocking rates, and planting years, and this alongside the variation between the sites themselves, makes statistical intra-planting comparison challenging. The approach taken in light of this was to focus on descriptive statistics (eg: Height, GLD, DBH and crown closure/diameters) of the plantings at time of measurement versus any available historical data, as well as to estimate the CO_2 sequestered on a per hectare basis for the bounded plantings (PSPs). As height was the most widely captured data historically, it's the one metric where growth trends can be estimated using LOESS regression of data captured to-date. These trends should still be considered in light of the data captured being at an early stage of growth for all plantings (even the oldest ones) and not representative necessarily of whole-life growth trajectory for most species. Where they utilise only two measurement years, they are unlikely to reflect true growth trajectories outside of the period modelled. Maximum possible heights by species for similar sites should therefore be considered alongside these regressions for context.

Despite the above points, there are also still confounding factors with regards to calculating growth and survival of the plantings, primarily the effect of animal browse damage and infill planting. Animal browse was noted but not quantified in this study for brevity, as much of the damage was historic (although there have variously been pigs, hare, and small numbers of deer trapped within the perimeter fence), although it likely had some impact on growth and compositional change depending on species targeted. Infill planting, which was not documented by year/area, was small in scale except for Plot 12-1, but will still lead to some underestimation of growth (arguably this is beneficial, as growth estimates will be conservative) and over-estimation of survival (negative as true mortality will not be reflected in the data captured). Carbon sequestration in tonnes per hectare was calculated as an indicative value for the bounded sites, but in general in will correlate with growth, stocking, and crown closure. When this data was aggregated for all the bounded plots and compared on a per-stem basis (kg/stem) ranges overlapped, suggesting no statistically significant difference for all but 3 of the sites (which could be attributed to infill planting or poor sites). This broad overlap (ranges were wide) being despite the varying growth periods of the sites (9 – 15 years) and the apparent better growing conditions of some older sites. There are two likely explanations:

- As the height growth rates were generally plateauing for most species on all sites, it may be that carbon sequestration is initially fast then slows – narrowing the differences between younger and older sites,

or

- The above ground biomass accumulation is too small for these species, at this relatively young age, to allow for statistically significant differences to be observed.

Planning for future planting on the site should make note of the relative growth rates and survival of species at the various sites identified in this report to inform species choice and mix, as well as pest control strategies should pest number increase following cull efforts. Key recommendations are:

- Increased planting of frost-tolerant species in frost-prone sites (eg: kohuhu, tarata)

- Maximising proportion of plantings of the fastest growing species for their respective optimal sites (eg: akeake and ngaio on sheltered sites and toe-slopes, ti kouka, manatu and kohuhu on wet sites, kanuka and black beech on more rapid draining mid-upper slope sites, etc.)

- Higher planting densities used on marginal sites to offset mortality and suppress competing exotic species (such as grasses) to reduce local inter-species moisture competition
    - Parallel to this: an appropriate mix of crown-form plantings (eg: fewer uni-stem, compact-crown species) should be used to ensure earlier crown closure

- A multi-stage planting programme should be used on some sites to increase success of generally slower growing, shade tolerant species (eg: matai, kahikatea)
    - This may take the form of 3rd or 4th year plantings (or later) into gaps and edges once the initial planting is established and can act as a nurse crop

- Seasonal soil moisture testing of proposed sites should occur prior to planting where possible, to assess species suitability

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